DREXEL UNIVERSITY Graduate College

DISSERTATION/THESIS APPROVAL FORM

This form is for use by all doctoral and master's students with a dissertation/thesis requirement. Please print clearly as the library will bind a copy of this form with each copy of the dissertation/thesis. All doctoral dissertations must conform to university format requirements, which is the responsibility of the student and supervising professor. Students should obtain a copy of the Thesis Manual located on the Graduate College or library website.

Dissertation/Thesis Title: Comprehensive Performance-Based Movement System Screening Tool for Athletes

Author: Courtney M. Butowicz, MSEd, CSCS

This dissertation/thesis is hereby accepted and approved.

Signatures:

Examining Committee

Chair

Members

JAMES ONATE 6/7/16

Academic Advisor Lisa A. Chiarello

Department Head Susan S. Smith

Graduate College 3141 Chestnut Street Main 301 Philadelphia, PA 19104
Tel: 215.895.0366 Fax: 215.895.0495 Email: graduatecollege@drexel.edu Web: www.drexel.edu/graduatecollege

(Last Updated 3/1/2016)

Comprehensive Performance-Based Movement System Screening Tool for Athletes

A Thesis

Submitted to the Faculty

of

Drexel University

by

Courtney Butowicz, MSEd, CSCS

in partial fulfillment of the

requirements for the degree

of

Doctor of Philosophy

June 2016

DEDICATIONS

This dissertation and all my hard works are dedicated to my family, friends, and my dog Cooper. Without their love, support, and laughter, this process would have never been possible.

ACKNOWEDGEMENTS

This dissertation was funded, in part, by the American Physical Therapy Association, Sports Section Legacy Fund Grant.

I would like to extend my gratitude to my committee members: Dr. Sheri Silfies, Dr. David Ebaugh, Dr. Clare Milner, Dr. Jimmy Onate, and Dr. Stella Volpe for their constructive and insightful feedback.

In addition, I would like to acknowledge and thank Dr. Sara Tomaszewski, Dr. Jeffrey O'Neill, and Dr. Sarah Wenger for their invaluable assistance and insight during the development of this dissertation project.

I cannot express enough gratitude to my advisor, Dr. Sheri P. Silfies for her mentoring, support, encouragement, and willingness to read and correct countless drafts of abstracts, proposals, manuscripts, and posters. Dr. Silfies gave me an opportunity to get involved and help in ongoing research projects, thereby considerably facilitating my learning process. I could not have completed this entire PhD process without her intelligence, guidance, and support.

I am thankful to PhD students: Dr. Pete Wattananon, Marisa Pontillo, Bryan Spinelli, Won Sung, Han Chen, Mike Bijman, and Trey Brindle for their support and encouragement throughout my PhD study. I would like to especially thank Won and Marisa for answering my endless questions and always providing me useful feedback from different perspectives based upon their clinical and research experiences.

Finally, I am deeply grateful to my mom and stepdad, Jan and Teddy Harris, for their unconditional love and support. And lastly, I would like to thank Erin and Jesse Crespo, Mindy Leher, Krista Tobin, and Jen Darley for being my family away from home and always being there for me throughout this process.

TABLE OF CONTENTS

LIST OF TABLES

CHAPTER ONE

CHAPTER TWO

CHAPTER THREE

LIST OF FIGURES

CHAPTER ONE

ABSTRACT

Comprehensive Performance-Based Movement System Screening Tool for Athletes

Courtney Butowicz, MSEd, CSCS

Sheri Silfies, PT, PhD

Musculoskeletal injuries can have damaging effects on sports and/or job performance, psychosocial factors, and an increased risk of musculoskeletal impairments later in life. Non-contact injuries, such as an ACL rupture or non-traumatic shoulder injury, account for nearly 40% of all injuries sustained during practices and 20% of injuries incurred during sanctioned games. Pre-participation movement screening has gained popularity in collegiate athletics and military personnel in efforts to identify poor performance and individuals potentially at increased risk of injury. Proposed risk factors for injury include impairments in regional stability (i.e. core stability), movement pattern efficiency, mobility, and symmetry. Impairments in any of these risk factors may influence force generation, transfer, and dissipation throughout the body, potentially increasing stress on segments and joints. Current movement screens provide limited assessment of core stability and upper extremity stability, movement pattern efficiency, and mobility. The purposes of this study were to: 1) describe a novel comprehensive performance-based movement system-screening tool (MSST), 2) determine the validity of common and novel clinical tests of core stability, 3) determine the psychometric properties of the MSST, 4) and determine the ability of the MSST to identify athletes with a current history of non-traumatic shoulder injury. Eighty athletes (40 with a current shoulder injury) completed the MSST and lab-based measures of isolated core stability. Findings demonstrated that none of the clinical tests of core stability within the MSST were moderately significantly correlated to our lab-based measures. Results of the exploratory factor analysis (EFA) revealed three of the four design constructs (proposed risk factors) over 7 factors, representing 63% of the variance accounted for within the MSST: movement pattern efficiency (lower extremity, dynamic lower extremity), regional stability (upper and lower extremity, trunk/pelvis, dynamic), and mobility (upper and lower extremity, trunk/pelvis). Individual test inter-rater reliability ranged from fair to perfect ($\kappa = 0.26 - 1.00$). Inter-rater reliability of the MSST composite score was excellent, ICC (2,1) = 0.94, 95% CI (0.91, 0.96). Athletes with non-traumatic shoulder injury (composite score = 56.5 ± 5.9) scored significantly lower than healthy controls (composite score = 59.5 ± 4.8) on the MSST ($t = 2.43$, $p = 0.02$, $d = 0.54$). Logistic regression revealed rotary stability, shoulder mobility dominant arm, and glenohumeral internal rotation deficit predicted whether or not an athlete had shoulder pain, $\chi^2 = 14.37$, $df = 5$, $N = 81$, $p = 0.01$. None of the clinical tests of core stability demonstrated acceptable construct validity ($r > 0.3$) for assessing core neuromuscular control in an athletic population. Assessments assumed to assess muscle capacity were not significantly correlated to our lab-based measures of isolated core neuromuscular control, suggesting they are assessing a different construct (muscle capacity). The results of the current study suggest the MSST may have adequate inter-rater reliability and construct validity for use in clinical settings. However, future work should be done to assess the test-retest reliability and predictive validity of the MSST. The MSST was able to discriminate performance differences in athletes with and without non-traumatic shoulder injury. To date, this is the first comprehensive movement screen used to address non-traumatic upper extremity injury in athletes.

CHAPTER ONE: PROPOSAL

ABSTRACT

Background: Musculoskeletal injuries can have a detrimental effect on sports performance, psychosocial factors, and an increased risk of musculoskeletal impairments later in life. Pre-participation screening has gained popularity in athletics in efforts to identify poor performance and those potentially at increased risk of injury. Regional stability, movement pattern efficiency, mobility, and asymmetry are proposed risk factors for upper and lower extremity injury. Impairments in any of these risk factors may result in performance degradations and inefficient force generation and transfer throughout the movement system. Current screening methods do not adequately assess core stability and upper extremity movement pattern efficiency and thus may not identify athletes at risk of non-traumatic upper extremity injury.

Purpose: The specific aims of this study are: 1) to describe a comprehensive performance-based movement system-screening tool, 2) determine the psychometric properties of the screening tool, 3) and determine the screening tool's ability to identify athletes with a current history of non-traumatic shoulder pain.

Design: Correlation, Methodological and Cross-Sectional

Methods: Eighty-four athletes (42 with current shoulder injuries) will complete the comprehensive performance-based movement screen. Athletes will also complete a lab-based measure of isolated core stability.

Data Analysis: The first aim will utilize a Delphi Technique to objectively reach consensus on screening items, item classification and scoring. The second aim will be

assessed using a Pearson's correlation, exploratory factor analysis, kappas, and intraclass correlation coefficient. Aim 3 will be assessed using an independent t-test and logistic regression.

Significance: Completion of these aims will provide clinicians with a comprehensive assessment of regional stability, asymmetry, and movement pattern efficiency. Furthermore, it will determine initial utility of the screen for identifying performance degradation associated with non-traumatic shoulder pain in athletes. Identification of performance decreases associated with injury allows clinicians to provide injury prevention training programs specifically designed to address noted movement impairments or imbalances. By decreasing the injury rates in sports, we can increase the overall health and wellness of the population by keeping individuals actively participating in all levels of sport.

SPECIFIC AIMS

Participation in collegiate athletics has increased significantly in the past 25 years and subsequently so have the number of injuries, with approximately 12,500 injuries reported each year.[1] Non-contact injuries, such as an ACL rupture or non-traumatic shoulder pain, account for nearly 40% of all injuries sustained during practices and 20% of injuries incurred during sanctioned games.[2] Injuries can have significant immediate and long-term effects on an athlete. These include, but are not limited to, degradations in athletic performance, the loss of participation in entire seasons, educational funding, decreases in academic performance, depression, disability, and increased risk of life-long musculoskeletal impairments.[3] Proposed risk factors such as impairments in *regional stability*, *movement patterns*, and *symmetry* are commonly associated with non-contact sports injuries.[4-9] Pre-participation sports screens are becoming more widely used in athletic settings to potentially identify risk factors for musculoskeletal injury as well as assess performance. Currently, there are a limited number of pre-participation screens that can be used for both injury prevention/risk assessment and athletic performance assessment.[10]

There is emerging evidence linking poor core stability to upper and lower extremity and low back injury in athletes.[9,11-16] *Core stability* can be defined as the ability to control the motion, position, and stiffness of the trunk and pelvis region relative to the extremities to allow for optimal force production, dissipation, and transfer to the distal segments during integrated kinetic chain movements.[6]

Regional stability may have a direct link to movement pattern efficiency or coordination. *Movement pattern efficiency* is defined as the coordination of motion (timing and amount) between segments and/or extremities to effectively accept, generate, or transfer forces to accomplish a skill or task. The kinetic chain model suggests that the core (comprised of the trunk, pelvis, and proximal extremity regions) is the mechanical link between the upper and lower extremities. This allows for the sequential coordination of segments to effectively generate, transfer and dissipate forces within the movement system.[17] Many movements in sport, such as those seen in throwing and racquet sports, require energy to be transferred from the hips and trunk to the upper extremities. Coordinated muscular activity through the core is essential for this sequence of energy transfer from the proximal to distal segments. The inability to produce, transfer, and dissipate forces effectively can lead to increased loads on the upper extremity, increasing the potential for injury.[6]

Theoretically, when a movement pattern or stability within the kinetic chain is altered, subsequent patterns throughout the system are also changed. These changes can create new or augmented stresses to the segments within the system, decreasing performance and increasing the risk of injury. Assuming any breakdowns in the chain can be attributed to core stability, poor core stability will result in compensatory movement patterns.[6] There is currently a lack of a screening tool that assesses stability and mobility throughout the system using validated core stability and upper and lower extremity movement pattern control tests. This gap limits the ability of clinicians to identify athletes whose performance has degraded relative to these proposed risk factors for injury.

The <u>long-term goal</u> of this research is to reduce athletic injuries. Initial steps that need to be accomplished are the development an assessment tool that assists clinicians in identifying athletes with degraded performance and increased risk of injury. The <u>overall</u>

objectives of this research project are to: 1) develop a comprehensive pre-participation screen for athletes by placing emphasis on assessment of core stability, movement pattern efficiency, and movement symmetry; 2) determine the psychometric properties of the screen; 3) determine ability of the comprehensive screen to identify athletes with non-traumatic shoulder pain. The central hypothesis of this research is that creating a comprehensive performance-based screen that emphasizes movement patterns and core stability assessment will enable clinicians to identify performance impairments commonly associated with athletic injuries.

We plan to accomplish the objectives of this application by pursuing the following 3 specific aims:

1. Describe a comprehensive performance-based movement system-screening tool for athletes.

1A: Utilizing the current literature and an expert panel, identify clinical tests that demonstrate evidence of injury prediction in athletes for the core, upper and lower extremity and select a comprehensive subset of tests.

1B: Describe newly developed clinical tests of core stability.

Working Hypothesis: New clinical tests can be developed and psychometric properties established in areas where current literature does not provide adequate assessment options.

2. Determine the psychometric properties of the comprehensive performance-based movement system screen.

2A: Determine construct validity of the clinical tests of core stability by validating the clinical core screening items within the comprehensive performance based screen against lab-based measures of core stability.

Working Hypothesis: A moderate to strong association will exist between concurrently assessed clinical tests of core stability and lab-based measures of core stability emphasizing neuromuscular control in an athletic cohort.

2B: Determine screen constructs and inter-rater reliability of tests within the comprehensive performance-based movement system screen.

Working Hypothesis: Core stability and lower and upper extremity movement patterns will be demonstrated constructs within the screen. Items within the screen will demonstrate moderate to strong inter-rater reliability.

2C: Determine inter-rater reliability of the composite score on a modified version (developed based on results of Aims 1, 2a, 2b) of the comprehensive performance-based movement system screen in a cohort of athletes.

Working Hypothesis: The composite score of the modified comprehensive screen will demonstrate moderate to strong inter-rater reliability in a cohort of athletes.

3. Determine the ability of the modified comprehensive performance-based screen to discriminate performance in athletes with and without non-traumatic shoulder pain.

3A: Determine the difference in composite scores on the modified comprehensive screen in athletes with and without non-traumatic shoulder pain.

Working Hypothesis: Athletes with non-traumatic shoulder pain will demonstrate poorer performance on the modified comprehensive pre-participation screen.

3B: Identify items in the modified comprehensive performance-based movement system screen that optimally classify athletes with and without non-traumatic shoulder pain.

Working Hypothesis: Test items related to assessment of upper extremity movement patterns and symmetry and tests of core stability will be the best tests to classify athletes with non-traumatic shoulder pain.

Completion of aims 1 and 2 will produce a comprehensive screening tool based on constructs of proposed injury risk factors. Additionally, it will provide evidence for the use of specific clinical tests to assess core stability directly. Completion of aim 3 is the first step in providing preliminary evidence of the tool's utility as a pre-participation screen to potentially identify athletes with non-traumatic shoulder pain or dysfunction. Using an assessment that addresses core stability and lower/upper extremity movement pattern efficiency will provide clinicians with a broad screen of the movement system. Potentially, this will ultimately assist clinicians in identifying movement impairments that represent degraded musculoskeletal performance and potential risk factors for athletic injury. Identifying specific impairments will aid in the development of training interventions to protect athletes from injury and improve athletic performance.

SIGNIFICANCE

Athletes perform high-speed, dynamic, and complex movements that require body segments to work synchronously to perform the skill or task. Theoretically, the ability to sequentially coordinate the forces between segments is critical for optimal athletic performance. Using the kinetic chain, the body can generate, transfer, and disperse forces between segments in order to perform these complex movements.[18,19] Decreased functioning of the force generators (muscles), altered muscle activation patterns, or breakdowns in the sequential transfer of force between segments may decrease athletic performance and increase injury risk.[18] Assuming that core stability is necessary for optimal coordination between segments, movement efficiency assessment should include both core stability and upper and lower extremity pattern assessment.

Sports practitioners and clinicians utilize screening tools to assess athletic performance and injury risk. Screens need to be both time-effective and cost-efficient, while providing comprehensive information about musculoskeletal performance, movement pattern efficiency, and the ability to identify individuals at risk of injury.[10] The Functional Movement Screen (FMS), 16-item physical performance measure screening battery (16-PPM), and Athletic Ability Assessment (AAA) are pre-participation screens proposed to qualitatively assess movement patterns, athletic performance capabilities. These screens are assumed to use multi-segment movements to identify breakdowns in the kinetic chain.[10,20-23] While the FMS focuses on global movement patterns, it provides limited assessment of core stability and upper extremity patterns. In order for clinicians to adequately assess musculoskeletal performance degradations in the extremities and the core, a valid and reliable comprehensive screen that assesses movement efficiency, bilateral symmetry, and core stability is needed. Development of this screen will be significant because it will provide clinicians a complete assessment of movement pattern efficiency, core stability, symmetry, and possibly identify performance degradations associated with injury. Identification of performance decreases associated with injury in athletes allows clinicians to provide injury prevention training programs specifically designed to address noted impairments or imbalances. By decreasing the injury rates in sports, we can increase the overall health and wellness of the population by keeping individuals actively participating in all levels of sport.

INNOVATION

The proposed research is innovative because it seeks to develop a screening tool based upon a novel conceptual framework that challenges current pre-participation assessment norms. Specifically, the proposed assessment will:

- be a validated and reliable comprehensive pre-participation screening tools that adequately assess both upper and lower extremity movement efficiency, core stability and bilateral symmetry.
- include validated measures of core stability. At present, much of the current research examining core stability and injury risk in athletes has focused on core muscle capacity via isometric endurance or strength measures.[4,13,24-26] To date, no study has validated currently used core stability clinical or screening tests. The lab-based measures outlined in this proposal will be used to validate current and newly developed clinical core stability tests. This lab-based measurement system isolates core stability with an emphasis toward assessment of neuromuscular

control by having an individual seated on an unstable surface and limiting any contribution of the lower extremities.[27] This seated paradigm uses a force plate data to calculate center of pressure (COP) parameters that represent control of the center of mass. From these parameters, we can then determine the ability of the individual to control the trunk and pelvis during dynamic movements without assistance from the upper and lower extremities.

- provide researchers with a screening tool that can be used in studies designed to investigate the theory linking impaired or degraded performance with upper extremity injury, as limited evidence currently exists within the literature.[16]

BACKGROUND

Scope of the Problem

Over 10,000 people in the United States seek medical care for musculoskeletal injuries sustained during sports, exercise, or recreational activities daily.[28] High school athletes account for an estimated 2 million injuries per year.[29] Overall, participation in sports is increasing yearly, with the National Collegiate Athletic Association (NCAA) reporting 372,933 athletes in 2002 and over 463,000 athletes in 2013.[30,31] Serious upper and lower extremity injuries are common in sports such as basketball, baseball, softball, volleyball, soccer, lacrosse, swimming, and field hockey. Anterior cruciate ligament injuries alone cost over $850 million in surgical costs each year, with another $2 billion spent on evaluation and rehabilitation.[32] Non-traumatic shoulder injuries, such as rotator cuff tendinitis and shoulder impingement syndrome, will affect nearly 30% of all overhead athletes, such as baseball and tennis players.[33] Upper extremity injuries account for nearly 75% of the time lost to injury in collegiate baseball players, with 69% of these injuries seen in pitchers.[34] Along with the high cost of treatment, injuries can lead to the loss of entire competition seasons, scholarship funding, decreased academic performance, long-term disability, and increased risk of osteoarthritis later in life.[3]

Musculoskeletal injuries also significantly affect the U.S. military population as they are a leading cause of disability among U.S. military personnel, with 90 % of all musculoskeletal injuries resulting from physical training and sports activities.[35-40] $548 million dollars in patient care costs were the direct result of approximately 2.4 million medical visits made to military medical treatment facilities as a result of musculoskeletal injuries in 2007.[41] Annually, there are more than 11 million limited duty days due to musculoskeletal injuries, with lower extremity injuries accounting for 4.8 million of these injuries.[42]

Asymmetry, movement pattern inefficiency, decreased core stability, and previous injury history are factors proposed to decrease performance and increase risk of musculoskeletal injury.[7,9,15,21,43-50] Secondary to the long-term effects of and costs associated with these injuries, there has been an increased interest in the ability to predict musculoskeletal injury in both athletic and military populations, with a focus on identifying movement patterns and bilateral asymmetries that potentially increase injury risk. Identifying which movement patterns or impairments are associated with decreased performance and injury risk will allow clinicians and trainers to address these patterns directly through a neuromuscular training and injury prevention program, possibly resulting in improved movement, dynamic balance, and regional stability.[51]

Conceptual Framework for Comprehensive Performance-based Assessment

As regional stability, asymmetries, injury history, and movement pattern efficiency are proposed risk factors for performance degradation associated with injury; it follows that an athletic performance and injury assessment should address these factors. Using the kinetic chain model (figure 1 below) as the framework for a comprehensive performance-based assessment, regional stability, symmetry, and movement pattern efficiency are be considered important layers within the foundation of human movement. Any alterations within these constructs may directly affect movement, mechanics, and/or ultimately performance of sports related tasks.

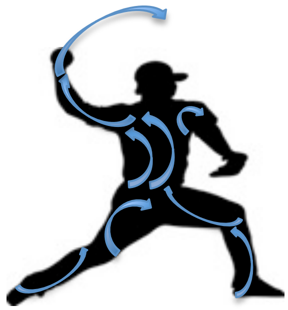


Figure 1. Kinetic Chain Model: The sequential link system creates an ideal environment for the efficient generation and transfer of force from the lower extremity to the upper extremity.

Movement System Approach

The American Physical Therapy Association (APTA) recently adopted a vision statement that emphasizes **movement pattern efficiency** and promotes the identification of human movement as a physiological system. This emphasis of improving movement through increased efficiency illustrates the importance of how movements occur, and the assessment of human **movement patterns**. The human movement system is defined as a "physiological system that functions to produce motion of the body as a whole or of its component parts; the functional interaction of structures that contribute to the act of moving."[52] The concept of multiple systems or segments working in coordination with one another to efficiently produce movement is directly related to Kibler's **kinetic chain theory**. Kibler suggests that the body's segments work in sequential coordination to produce, transfer, and generate energy during sport skills. In order for this to occur, the **core** (lumbo-pelvic-hip complex) must have **optimal stability** (**neuromuscular control** and **muscle capacity**) to accept and transfer this energy. While the core may be responsible for transferring energy between the distal segments, the efficiency (stability and mobility) with which the upper and lower extremities move is equally important when assessing the system. Impairments in distal patterns may be seen or reflected in other segments of the system. In order to assess the efficiency of the movement system, clinicians need to be able to assess efficiency in the extremities, as well as stability in static and dynamic tasks. The assessment should challenge the athlete in varying degrees of demand in an attempt to mimic the challenges incurred during sport.

Operational Definitions of Key Terms

Performance: execution of a physical task or skill in accordance with expected standards of efficiency, speed, accuracy, and completion. Athletic/musculoskeletal performance lies on a continuum of optimal to deteriorated/degraded performance with degraded performance considered as either the result of or causing injury.

Movement pattern: coordination of motion between segments and/or extremities during tasks.

Movement pattern efficiency: the coordination of motion (timing and amount) between segments and/or extremities that demonstrates effective acceptance, generation, or transfer of forces to accomplish a skill or task. For bilateral tasks, this includes equal motion and weight bearing through the extremities.

Stability: The ability to control the body region's position in order to withstand internal and external perturbations.

Kinetic chain theory: suggests that the core (comprised of the trunk, pelvis, and proximal lower extremity) is the mechanical link between the upper and lower extremities, allowing for the sequential coordination of segments to effectively generate, transfer and dissipate forces within the movement system.[17]

Core region of the body: the musculoskeletal combination of the trunk (including spine and abdominal region), pelvis, hips, and proximal extremity.[6]

Core stability: the ability to control the motion, position, and stiffness of the trunk and pelvis relative to the extremities to allow for optimal force production, dissipation, and transfer to the distal segments during integrated kinetic chain movements.[6] Theoretically, optimal core stability requires both neuromuscular control and muscle capacity of the core musculature.

Core neuromuscular control: the ability to accurately orchestrate a synchronized muscular response to internal and external perturbations based on sensory feedback information to control position or motion (i.e. joint position, velocity, pain, pressure).[53]

Core muscle capacity: strength, endurance, and/or power of the muscles that encompass the musculoskeletal core.[16]

Asymmetry: an anatomical, movement pattern, strength, mobility or stability difference between left and right sides of the body.

Non-traumatic shoulder pain: shoulder pain that is not caused by a single trauma or event of excessive force (macrotraumatic), with onset of the injury or pain in the last 6 months.

Athlete: any individual currently competing in any sport at a professional, semi-professional, varsity, junior varsity, or club level, with a minimum participation of 10 hours per week in practice and/or strength and conditioning workouts.

Comprehensive performance-based movement system screening tool: a compilation of upper extremity, lower extremity, and core stability tests that assess symmetry and movement pattern efficiency. The working title of this screen is the Movement System Screening Tool (MSST).

Expert: A clinician, practitioner, or scientist with a comprehensive knowledge and experience in orthopedic movement assessment. Specifically, experts must possess any of the following certifications: Orthopedic or Sports Specialist Certification (OCS/SCS-PT), certified Athletic Trainers (ATC), FMS/SFMA Certification, and/or Strength and Conditioning Specialist Certification. Experts should have a minimum of 2 years post-graduation training.

Kinetic Chain Theory

Kibler's kinetic chain theory was established based on a combination of biomechanical and motor control theories.[54,55] The kinetic chain theory was developed in an effort to explain how various segments of the body coordinate with one another to accomplish complex and skilled tasks. The kinetic chain model presents a mechanism by which the body generates, transfers, and disperses forces between segments, using the core, in order to perform the complex dynamic movements often seen in athletics.[18,19] The ability to sequentially coordinate the forces and energy generated from one segment and translate them through the core to another segment is critical for optimal athletic performance. In order for the chain to be effective, core function, motor patterns, strength/endurance, and mechanics must all be optimally developed [18], where as decreased functioning or breakdowns in the sequential transfer of forces may decrease athletic performance and increase injury risk. Identifying deviations from the expected movement performance may enhance injury risk assessment because it provides the clinician with specific information that can be used to address the breakdown via the development of a neuromuscular training program.

Regional Stability

Based on Kibler's kinetic chain theory, the core region of the body is critical for optimal force transfer between the lower and upper extremities. The core of the body can be defined as the musculoskeletal combination of the trunk (including spine and abdominal region), pelvis, hips, and proximal lower extremity.[6] While there is no universally accepted definition of core stability, several researchers have attempted to define the concept. Panjabi illustrated the concept of core stability as three subsystems: the passive spinal column, active spinal muscles, and a neural control unit.[56] The passive system includes vertebrae, discs, joints and ligaments of the spine.[56] The muscles and tendons surrounding the spine make up the active system, while the sensory and motor neurons associated with the structures in the passive and active system form the neural subsystem.[56] Liemohn et al (2005) defined core stability as "the functional integration of the passive spinal column, active spinal muscles and the neural control unit in a manner that allows the individual to maintain the intervertebral neutral zones within physiological limits, while performing activities of daily living."[57] Kibler et al (2006) defined core stability as the ability to control the motion and position of the trunk over the pelvis and extremities to allow for optimal force production, dissipation, and transfer to the distal segments during integrated kinetic chain movements.[6] Theoretically, core stability requires the ability to control the trunk, in relation to the extremities, using information from the nervous system, in response to internal and external forces.[16,58] Optimal neuromuscular control and muscle capacity (strength and endurance) are critical components of core stability.[16] Neuromuscular control is the ability to accurately orchestrate a synchronized muscular response to internal and external perturbations based on sensory feedback information (i.e. joint position, velocity, pain, pressure).[53] The muscles and structures of the core are centrally located within the body and serve to stabilize the body for optimal functioning of the extremities.

The Relationship of Performance-based Constructs to Injury in Athletes

Asymmetry, Performance and Injury

Asymmetries, including strength imbalances, are proposed risk factors for musculoskeletal injury.[59-63] Knee flexor strength differences greater than 15% and hip extensor flexibility greater than 15% bilaterally were associated with increased risk of lower extremity injury in female collegiate athletes.[61] Long distance runners with illiotibial band syndrome (ITBS) demonstrated decreased hip abduction strength on the affected limb when compared to the non-affected limb and healthy controls.[60] Untreated hamstring strength imbalances increased the relative risk (relative risk: 4.66; 95% CI: 2.01-10.8) of musculoskeletal injury in professional soccer players.[49] Increased hamstring to quadriceps ratio (H:Q) when measured isokinetically at 90°/s was associated with increased risk of non-traumatic overuse injuries in soccer players (OR: 1.13).[64] However, decreased H:Q when measured at 300°/s was reported as associated with increased incidence of non-traumatic overuse knee injuries in collegiate female athletes.[65] While there is evidence to support the presence of a muscular strength and flexibility imbalance as a risk factor for non-traumatic lower extremity injury, future research is needed to better understand the relationship.

Regional Stability, Performance and Injury

Impairments in core stability have been linked to low back and upper and lower extremity injury.[9,11-13,15,66] Competitive swimmers with shoulder pain exhibited significantly less core endurance compared to non-symptomatic swimmers.[13] Delayed trunk muscle reflex responses are reported to be predictive of low-back injuries in athletes.[11] Impaired core proprioception and the ability to regain control after perturbation were predictive of knee injury in athletes [9,15]. Increased lateral trunk motion is seen in female athletes during an ACL injury when compared to male and female controls that demonstrated similar patterns during jump landing or cutting tasks.[44] Decreased hip abduction and hip external rotation strength is associated with patellofemoral pain in females and predicted lower extremity injury in collegiate basketball and track athletes.[4,12] Therefore, an athlete that is unable to control the displacement and velocity of the trunk, which consists of over half of an individual's overall mass, during dynamic movements suggests that they lack the core control or condition to adequately accept and transfer the internal and external forces generated in athletic activities.

Athletes perform high-speed movements that often put the body into positions that are less than optimal to receive, dissipate, and generate force. The athlete's ability to control the core and the center of mass during these movements relies heavily on the muscles of the trunk, hips, and pelvis. Adequate neuromuscular control and muscular condition are necessary for the core musculature to perform appropriately. From a control perspective, the system must have accurate and complete feedback from sensory receptors to the CNS. The sensory information must be accurately transmitted to and from the CNS and the muscles must have adequate condition to respond to feedback received from sensory input.[53] In a recent prospective study, baseball pitchers with decreased lumbopelvic control were 3 times more likely to miss at least 30 days due to injury.[66] Lumbopelvic control was measured by assessing the amount of anterior-posterior lumbopelvic motion using a single-leg raise test, in which the individuals were asked to keep their waist as level as possible as they lifted one foot to a step. Decreased lumbopelvic control may disrupt the efficient generation or transfer of energy from the lower to the upper extremity, leading to an altered pattern. This could create excessive forces through the upper extremity in an attempt to create increased ball velocity in baseball pitchers.[66]

Trunk muscle activity has been demonstrated to consistently activate prior to movement of the extremities, suggesting that these muscles are providing support to prepare for acceptance of forces from the distal segments.[67] The abdominal muscles co-contract with the lumbar extensors to provide overall stability of the trunk.[68] Alterations in timing or activation patterns of the trunk musculature may affect trunk stability, as the proximal segment is not able to adequately generate or transfer forces from the distal segments. Altered timing patterns may affect positioning of the distal segments, placing them in suboptimal positions for force acceptance from the proximal structures. Hirashima et al (2002) demonstrated that the proximal musculature of the trunk was activated prior to the distal musculature during a throwing motion similar to a baseball pitch.[69] This supports the theory that force is transferred from the proximal to distal segments via sequential muscular activation from the trunk to upper extremities.

The abdominal muscles control anterior pelvic tilt, which is associated with femoral internal rotation and adduction, both of which are reported risk factors for knee injury.[7,70,71] When the core musculature is unable to provide stability to the trunk and pelvis, the ability of the system to transfer forces between upper and lower extremity segments may become compromised. It is then possible that the extremities are exposed to increased forces and become vulnerable to positions of decreased mechanical efficiency and potential injury.[72] Hong et al (2001) examined patterns of muscular moments and interactions between segments (lower extremity, trunk, and upper extremity) during a throwing motion in baseball pitchers.[73] Results demonstrated that the trunk rotators accelerate, causing a moment about the upper trunk, which then causes acceleration of the upper extremity, supporting the proximal to distal theory of sequential force generation.[73]

Movement Pattern Inefficiency, Performance and Injury

Movement patterns are key factors that have the potential to influence the risk of musculoskeletal injuries. Based on the kinetic chain model, optimal movement pattern efficiency is dependent upon core stability, overall muscle capacity (strength/endurance), and neuromuscular control.[16] Impairments in any of these components can cause an altered or inefficient movement pattern, creating deviations from the expected or optimal performance of a task. These deviations may result in the inefficient generation, transfer, and dissipation of forces throughout the body. This inefficient transfer may alter movement patterns throughout the kinetic chain; potentially placing added stress to distal joints and segments. Movement pattern efficiency can be assessed using functional tests designed to assess the multi-joint stability and mobility throughout the kinetic chain during dynamic tasks such as those seen in sport. Considering stability and mobility are critical components, these tests should assess regional stability and mobility independently as well as collectively.

One example of a movement-screening tool that has gained popularity among clinicians and sports performance specialists is the Functional Movement Screen (FMS).[10,14,25] The FMS is based on a framework supported by the kinetic chain theory, integrating sequential physiologic muscular patterns into human movement.[20,21,74] The FMS was designed to challenge multi-joint mobility and stability during commonly seen movement patterns in sports, such as squatting and lunging.[21] The FMS uses 7 fundamental movement patterns to quantify the quality of movement performance and identify compensatory patterns within the system. While the focus of the assessment is on global movement patterns, Cook et al (2006) suggest that the FMS requires segments to work in a proximal to distal sequence.[21] This would support the concept of core stability being necessary for efficient production of the movement patterns within the FMS. The ability to control the trunk in relation to the pelvis and extremities in a combined movement is required for the deep squat, in-line lunge, hurdle step, and rotational stability tests.

Assessment of the Performance-based Constructs

Assessing Asymmetry

Asymmetry can be evaluated through the assessment of strength and/or dynamic performance. Clinically, muscle strength can be measured statically using a subjective score on a manual muscle test (MMT) or objectively by using a hand-held dynamometer.[75] Performance on dynamic functional tasks (such as the Y-Balance Test, Single-Leg Hop, step down test, and items within the FMS) can be used to assess side-to-side differences in lower extremity movement patterns.[76-79]

Assessing Regional Stability

Clinically, regional stability of the core is commonly assessed using measures of muscle capacity. Assumedly, optimal core stability requires a combination of muscle capacity (endurance and strength) and neuromuscular control of the core musculature. Neuromuscular control of the core represents the ability of the neuromuscular system to respond to proprioceptive stimuli to alter the position of the trunk and pelvis to maintain stability.[53] Core endurance tests reported in the literature primarily utilize isometric hold times to quantify muscle capacity. While these tests may not be functionally applicable to sports performance, they are repeatable, do not typically require expensive equipment and can be done almost anywhere. McGill et al (1999) published normative endurance times for healthy men and women for the trunk side bridge, flexor, and extensor tests in an effort to provide clinicians with a reference point when assessing core function clinically.[24] Trunk extensor normative values for healthy adults were reported as 171 +/- 60 seconds, with reported test-retest reliability ranging from ICC= 0.54-0.99.[80] Trunk flexor normative values for healthy adults were reported as 147 +/- 90 seconds.[24] Lanning et al (2006) reported normative values for trunk endurance and hip strength in collegiate athletes using a 60s back extension test, 60s tall kneeling test (to assess eccentric strength of illiopsoas and rectus femoris), isometric hip internal rotation strength (using a dynamometer), and double-straight leg lowering test (DLLT) to provide clinicians baseline values of core function to compare among athletes.[81] The DLTT has reported test-retest reliability ($ICC_{3,1}$= 0.98) [82] and ($ICC_{2,1}$=0.63) [81] with a mean score of 50 +/- 10 degrees for collegiate athletes.[81] The DLLT assesses an individual's ability to control the position of the pelvis while lowering their legs from 90° of hip flexion. The test requires the individual to maintain pressure in a sphygmomanometer placed under the lumbar spine and a wall goniometer (Appendix 1). Once the pressure changes 10 mm Hg, the angle of the legs relative to the horizontal is recorded. The equipment requirement for the DLLT may be a potential limitation to its practicality as a screening tool to assess core stability.

Table 1. Normative Values and Reliability for Common Core Stability Tests

Test	Population	Reliability	Normative Means (SD)	Reference
Double Leg Lowering	College Athletes	*ICC: 0.63– 0.98	50° (10)	Krause et al 2005; Lanning et al 2006
Flexor Endurance	Healthy Adults	**ICC: 0.98	147s (90)	McGill et al 1999: Evans et al 2007
Extensor Endurance	Healthy Adults	*ICC: 0.54-0.99	171s (60)	McGill et al 1999; Moreau et al 2001
*Indicates test-retest reliability reported **Inter-rater reliability reported				

Laboratory based biomechanical assessment (including kinematics, kinetics, and center of pressure trajectories) of the trunk and pelvis during unstable sitting has been used to quantify core stability in athletes and individuals with low back pain [9,15,27,83]. Core stability, specifically neuromuscular control, can be isolated by measuring control of center of pressure during unstable sitting, thus reducing influence of the lower extremities by supporting the legs and feet.[27] Cholewecki et al (2000) designed an unstable sitting apparatus that removed the influence of lower body corrections by using leg and foot supports attached to the unstable surface itself and placed the apparatus on top of a force plate.[27] A hemisphere was attached to the bottom surface of the seat to create an unstable surface, requiring active control of the trunk and pelvis to maintain balance, while center of pressure (CoP) data were quantified using the force plate measurements. CoP, sometimes referred to as body sway, has been used in posturography to assess postural control. The 95% Confidence Ellipse (CEA) represents 95% of the area that CoP traveled during the test. A larger CEA represents less control of the body's center of pressure. The mean velocity (MVEL) represents the mean displacement of the CoP per second. A larger MVEL suggests that the individual became unstable during the test and over corrected quickly to return to a stable position and avoid falling. Therefore, a smaller MVEL would suggest better stability when compared to a larger MVEL. Center of pressure data allow us to quantify the neuromuscular control aspect of core stability. This model allows us to isolate and quantify neuromuscular control of the core in the laboratory; however, there is currently no published clinical assessment that focuses on this aspect of core stability.

Assessing Movement Pattern Efficiency

Current pre-participation movement screens attempt to quantify movement patterns and identify individuals at risk of injury based on dysfunctional patterns.[22] Common screens include the FMS, 16-item physical performance measure (16-PPM), and Athletic Ability Assessment (AAA).

The utility of the FMS as a reliable and valid measure of functional movement is integral to the successful implementation of the assessment into pre-participation screens. Each test is scored on a 0-3 scale (0 for pain during the test, 1 for major compensations or deviations, 2 for minor compensations or deviations, 3 for perfect performance) with the final score of all bilateral tests being the lower of the two tests. The final score is then tallied and used as a composite score. Test-retest reliability of the FMS using a single rater has been reported as good to excellent (ICC = 0.6 – 0.92).[84] Interrater reliability was reported as substantial to excellent (kappa = 0.74-1.0, ICC = 0.92 – 0.98) when using novice and expert raters.[10,85] Criterion validity of the grading of the FMS was assessed by comparing expert raters' live real-time scores to that of an objective inertial-based motion capture system.[86] Kinematic thresholds were developed that corresponded to the specific grading criteria of each test. Agreement between the objective measurement and live grading was poor in the six FMS tests used, with weighted kappas (k_w) ranging from 0.05 to 0.52. This poor agreement could be representative of a lack of concurrent validity of the observation/scoring system of the FMS, as the subjective scores did not reflect the corresponding objective (kinematic) scores. One possible suggestion for this lack of agreement could be that inappropriate kinematic values were established in the objective measure. Whiteside et al. (2014) suggests that the low agreement between objective and subjective scores suggests that the scoring/grading of the FMS is susceptible to error and caution should be used when considering the FMS score as a predictor of injury or the basis for a strength and conditioning program.[86]

An FMS score (range 0-21) ≤ 14 has been reported to predict lower extremity injury in professional football players, collegiate athletes, military personnel, and first responders.[50,87-91] However, there is conflicting evidence regarding the utility of the FMS as an injury risk prediction tool.[92-97] Recent evidence indicates a mean score of 14.2 ± 2.9 for general population individuals ages 20-64 and a mean score of 15.7 ± 1.9 for athletes ages 18-40.[98,99] Assuming that athletes exhibit better movement pattern efficiency compared to non-athletes, this lack of variance in the scores among different populations may limit the ability of the FMS to effectively discriminate athletic performance.

Several researchers have examined the ability of the FMS to predict injury in athletes. In professional football players, Kiesel et al (2007) assessed the ability of the FMS to predict serious injury (N=46) over the course of a season.[87] An injury was defined as an event that caused a player to be placed on the injured reserve list and a time loss of 3 weeks. Based on the coordinates of an ROC curve, with a sensitivity of 0.54 (CI95= 0.34-0.68) and specificity of 0.91 (CI95= 0.83-0.96), a cutoff score of 14 was considered to be predictive of injury (≤ 14). The average score for players sustaining an injury was 14.3 ± 2.3 and 17.4 ± 3.1 for players who were not injured. The calculated odds ratio of 11.67 suggested that an athlete scoring a 14 or less was eleven times more likely to sustain an injury. However, the study only looked at professional football players and used a specific injury definition that captured significant injuries that resulted in the loss of at least 3 weeks of playing time.

Chorba et al (2010) determined the FMS' ability to predict lower extremity injury in female collegiate athletes (N=38) [50]. An injury was defined as any musculoskeletal injury that occurred as a result of an incidence in a sanctioned game or practice and required medical attention from any member of the sports medicine staff. Using the same cutoff score of 14 from the Kiesel et al (2007) study revealed that 69% of the athletes scoring below a 14 sustained an injury and were four times more likely to sustain an injury. They concluded that the FMS could predict injury in female athletes without a history of major injury. However, this study did not generate its own cut score for this population. Interestingly the mean score for all athletes in the study was 14.3 ± 1.8, which is remarkably close to the cutoff score of 14 developed in the Kiesel et al study [87] using a different sample and operational definition of injury.

Garrison et al (2015) examined the association between FMS scores, injury history, and the risk of injury in 160 collegiate athletes.[91] Authors used a broader definition of injury to include any musculoskeletal pain complaint (at rest or during activity) with the following criteria: injury was associated with physical activity, required the athlete to seek the advice of a medical professional, and the injury required a minimum of 24 hours of modified activity or prophylactic bracing/taping for further activity. Based on the coordinates of an ROC curve, with a sensitivity of 0.67 and specificity of 0.73, a cutoff score of ≤ 14 was predictive of injury in this cohort of athletes. Calculated odds ratios of 5.61 (95%CI: 2.73-11.51) at this cutoff score suggest that an athlete who scores ≤ 14 on the FMS is 5 times more likely to sustain an injury. While injury history is a reported risk factor for injury, the combination of an FMS score ≤ 14 and the history of at least one sports related injury increased the odds ratio to 15.11 ((95% CI: 6.60-34.61). This data suggest that an athlete with an FMS score of ≤ 14 and a history of musculoskeletal injuries will be 15 times more likely to suffer an injury when compared to an athlete with a higher FMS score and no previous injuries. It should be noted that the broad injury definition used in this study might have affected the results as some injuries may have not resulted in a loss of playing time, yet, were thought to possibly affect performance and/or utilized medical staff and resources.

Firefighters are also reported to have an increased risk of musculoskeletal injuries, prompting Butler et al (2013) to examine the ability of the FMS to predict injury in 108 firefighters.[89] Firefighters completed a series of physical performance tests and the FMS prior to entering the firefighter-training academy and were then tracked for injury over the course of the training. Authors defined injury as “any episode that caused the recruit to miss 3 consecutive days of training in the academy due to musculoskeletal pain (excluding burns)."[89] Based on the coordinates of an ROC curve, with a sensitivity of 0.83 and specificity of 0.62, a score of ≤ 14 was identified as the cut point to differentiate between firefighters who sustained an injury and those who did not with 77.8% accuracy. This cut score demonstrated an OR: 8.31 (95%CI: 3.2 – 21.6) and positive LR of 2.20 and negative LR of -0.26.

Similar to collegiate athletics, musculoskeletal injuries are a significant problem in active duty military personnel with approximately 25% of males and 50% of females likely to experience at least one musculoskeletal injuries during basic training alone[37] In an effort to examine the utility of the FMS to predict musculoskeletal injuries in a cohort of U.S. Coast Guard cadets, Knapik et al (2015) tested 770 male and 275 female cadets on the FMS and then tracked injuries during an 8-week physical training cycle.[88] The average total FMS score for the males was 14.5±1.9 and for the females, 15.1±1.9. Using an ROC curve analysis, with areas under the curve of 0.53 for men and 0.59 for women, a Youden index score revealed optimal sensitivity and specificity of FMS total score cut points to be ≤11 for men and ≤14 for women. Further analysis revealed the prognostic accuracy of these cut points to be low, accurately predicting 22% of males injured and 60% of females. While the results of this study overall demonstrate that as the FMS total score decreased, the likelihood of injury increased, the poor ability of the FMS cut points designated from the ROC analysis to accurately predict injuries supports the need for further investigation into the FMS' utility as a pre-participation screen for injury risk.

While there is some evidence to suggest the utility of the FMS to predict injury, evidence to challenge this finding remains. Burton (2006) investigated the ability of the

FMS, VO2max, 1.5 mile run time, and a firefighter performance measure to predict injury in a cohort of 23 firefighter trainees over the course of a 16-week training program.[92] Logistic regression results suggested that the firefighter performance measure was the only significant predictor of injury in this cohort. Interestingly, the average FMS score in this study was 13.6 ± 2.0, which is below the score of 14, which has been suggested as a cut score for injury risk.

Morell (2012) examined the ability of the FMS and Star Excursion Balance Test (SEBT) to predict lower extremity injury in collegiate football players (N=108) [94]. While the injured athletes scored lower on both the FMS and SEBT, only the SEBT anterior reach score was statistically significantly different between injured and non-injured groups ($p=0.04$). ROC curve coordinates, with a sensitivity of 0.42 and specificity of 0.72, revealed an FMS cut score of ≤ 15.5 produced an odds ratio of 2.08, suggesting that football players who score below a 15 (15.5 is not possible) are twice as likely to suffer an injury as a player who scores above a 15. Interestingly, an SEBT anterior reach score of ≤ 71% of an individual's leg length increases that individual's risk of injury by 4 times, suggesting the SEBT anterior reach is a better predictor of injury risk than the FMS total score.

Further evidence to contradict the utility of the FMS as a predictive injury risk assessment is demonstrated by its lack of ability to accurately predict injury in a cohort of high school basketball players.[96] Sorenson (2009) assessed the ability of an FMS score of ≤14 to predict injury in 112 (52 male, 60 female) high school basketball athletes.[96] Any injury that was considered "contact" by nature (i.e. caused by contact with another player, the ground/floor, or ball) was not used in the analysis. Only injuries reported to or witnessed by the team's athletic trainer in a sanctioned practice or game were recorded. There were no statistically significant differences between male and female players, thus the scores were pooled for analysis. The average FMS total score in this cohort was 14.5 ± 2.1, which is markedly close to the cutoff score of ≤14 suggested to predict injury. Using the cutoff score of ≤14 was not associated with an increased risk of injury in high school basketball players ($x^2 = 0.03$, $p > 0.5$). It was noted that 22% of the athletes who scored ≤14 were injured, while 24% of the athletes who scored ≥ 14 were injured. The results of this study further support the need for a better assessment of injury risk in athletes.

Normative values for the FMS have been published in populations of healthy adults and middle-aged women. Schneiders et al (2011) established normative values for FMS scores in young healthy individuals.[99] Two hundred nine individuals between the ages of 18-40 with no history of musculoskeletal injury in the last 6 weeks underwent FMS testing. The mean score of all participants was 15.7 ± 1.9. Perry and Koehle (2013) established normative values in middle-aged adults, ages 20-65.[98] Six hundred twenty two (395 males, 227 females) urban-dwelling participants performed the FMS. The overall mean score for both males and females was 14.2 ± 2.8. Females between the ages of 20-39 averaged 15.4 ± 2.4, while their male counterparts averaged 14.8 ± 2.8. Results of these normative value studies combined with the mean scores of the athletes tested in the Kiesel et al (2007) and Chorba et al (2010) expose a potential weakness of the FMS. Theoretically, collegiate athletes and professional football players should demonstrate increased efficiency and coordination of fundamental movement patterns because they perform these patterns on a daily basis within the demands of their sport and training routines and are in peak physical condition. However, the results of these studies reveal that non-athletes may perform as well or better than elite athletes on the FMS. Reasons for this disparity could be due to scoring error between raters, or a testing and scoring structure that is not challenging enough or broad enough in skill level. Thus resulting in a lack of variance in the composite FMS score. The small variance in FMS score range among different populations, coupled with contrasting evidence supporting its ability to predict injury, supports the demand for a novel comprehensive screen to assess athletic performance and injury risk.

With a majority of the tests focusing on lower extremity patterns, it is possible the FMS does not challenge upper extremity movement efficiency and core stability sufficiently to distinguish individuals with varying capacity in the core and upper extremity. A survey of sports performance practitioners revealed that a majority preferred to utilize personally developed movement assessments as opposed to the FMS. This suggests that the FMS may not meet the perceived movement assessment requirements of these practitioners.[100] Further research is needed to better understand the role of upper and lower extremity movement efficiency and core stability in pre-participation screens designed to predict injury and discriminate between individuals with impaired movement patterns.

In summary, the FMS demonstrates good to excellent inter-rater and test-retest reliability. The evidence to support the utility of the FMS as an injury prediction tool remains controversial, as there are a similar number of studies both supporting and opposing its ability to predict injury in a variety of cohorts. Combined with published normative data reporting an average FMS score ranging from 14.7-15.7, the ≤ 14 cut point for injury risk prediction appears to fall within the standard deviation/standard error of many of the reported averages.

The 16-PPM expands on the movement pattern assessment construct of the FMS by incorporating quantitative measurement of strength, endurance, power, and motor control.[22] The 16-PPM includes the following tests: full squat (FMS), downward dog, broad jump, closed kinetic chain upper extremity stability test (CKCUEST), Y-Balance Test (YBT), in-line lunge for distance, lumbar endurance, single-leg squat, shoulder mobility test (FMS), active straight leg test (FMS), side plank hip abduction, Beighton Hypermobility, triple hop for distance, Nordic hamstring, lateral lunge for distance, and side plank hip adduction. Tests are scored either on a continuous (quantitatively) or ordinal scale (qualitatively). Qualitatively scored tests included the full squat, downward dog, sing-leg squat, active straight leg raise, shoulder mobility, and Beighton hypermobility. Tests were scored on a 0-5 scale, with 0 indicating pain with any portion of the test and 5 indicating perfect performance. Scores 1-4 are test dependent and typically follow that a lower score (i.e. 1) is representative of more errors, more limitations, or poorer overall performance. A majority (8 of 10) of the quantitatively scored tests demonstrate good expert-novice inter-rater reliability (ICC > 0.75) and test-retest reliability (ICC > 0.70).[22] Qualitative tests demonstrated slight to substantial interrater agreement (kw=0.26-0.93) and test-retest reliability (kw = 0.30-0.81).[22]

The Athletic Ability Assessment (AAA) utilizes increased levels of load and movement complexity to assess an athlete's ability to respond to increased stress or demand.[23] The AAA includes the following tests: prone plank, side plank, overhead squat (FMS), single-leg squat off box, walking lunge with barbell, single-leg hop, lateral bound, pushups, and chin-ups. Each movement is scored based on three main assessment points that are task dependent (1-3 scale). For example, the prone hold's assessment points include the position of the upper back/shoulder during the test, the hip position, and the time held. A score of 1 indicates poor movement or inability to complete the task, a 2 represents inconsistent performance or minor deviations, and a score of 3 indicates perfect performance. The sum of scores for each assessment point is used as the score for that particular test. Unilateral tests are given separate scores. The total possible composite score is 117 points. McKeown et al (2014) reported fair to substantial inter-rater agreement (κ = 0.33-0.77), poor to high intra-rater reliability (ICC = 0.53-0.90), and an inter-rater minimal detectable change score of 2.8 (90% CI: 2.5-3.3) for the composite score. It should be noted that the reliability values reported by McKeown et al (2014) were based on a small sample (N=17) of female soccer players. Thus, at this time, the reliability and validity of the AAA in other athletes is unknown.

Individual Clinical Assessments with Evidence of the Ability to Predict Injury

While evidence supporting the predictive capabilities of movement pattern assessments is conflicting, individual upper and lower extremity, hip strength, and core stability assessments have demonstrated injury predictive capabilities. Glenohumeral internal rotation deficit (GIRD) is defined as at least a 15-degree loss of IR combined with a loss of at least 10-degrees of total arc of motion of the throwing shoulder when compared to the non-throwing shoulder.[101] In a cohort of professional baseball players, pitchers with GIRD (n = 40) were nearly twice as likely to be injured as those without GIRD.[102] Injured pitchers demonstrated significantly less dominant arm IR ($p<0.004$), while players with UCL insufficiency demonstrated significantly less GIRD (28.5° vs

12.7Æ; P < .001). Total range of motion was significantly decreased in the injured group.[103]

Figure 2. Glenohumeral Internal Rotation Deficit (GIRD): A) Passive internal rotation measurement; B) Passive external rotation measurement.

The Y-Balance Test (YBT) is an assessment of dynamic postural control in single-leg stance, with supporting evidence as a predictor of lower extremity injury in athletes.[104,105] The YBT requires an individual to maintain single-leg stance while reaching as far as possible in either the anterior (ANT), posteromedial (PM), or posterolateral (PL) directions with the contralateral leg. The test-retest reliability of the YBT has been reported to range from 0.78 to 0.96.[106] Athletes with an anterior reach difference between sides of greater than or equal to 4 cm have an increased risk of lower extremity injury (odds ratio: 2.3,95% confidence interval, 1.15–4.76).[104,105]

Figure 3. Y-Balance Anterior Reach Test (Shown: YBT left): Athlete stands in single-leg stance with the great toe of the stance foot at the start line of a tape measure. While maintaining the hands on the hips and the stance heel on the ground, the athlete is required to reach forward with the non-stance limb and touch the furthest portion of the tape possible.

The closed kinetic chain upper extremity stability test (CKCUEST) provides objective data for functional upper extremity performance.[107-109] The CKCUEST is a functional clinical test that requires stability, strength, and speed. The test requires an athlete to maintain the top position of a push-up while simultaneously moving the upper extremities from one tape line to another (36 inches apart) as many times as possible in 15 seconds. Normative values for female collegiate athletes are reported as an average of 21.8 ± 3.9 touches, while male collegiate athletes averaged 26.0 ± 4.1 touches.[110] Collegiate football players who score less than 21 touches in the 15s time period are at an increased risk to sustain a shoulder injury (odds ratio: 18.75, 95% confidence interval, 1.68-209.55).[108]

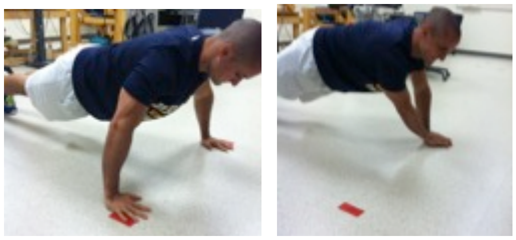


Figure 4. Closed Kinetic Chain Upper Extremity Stability Test (CKCUEST). Athletes alternate touching one hand to the other as many times as possible in 15 seconds. Athletes must maintain the top position of a push-up during the test.

The Active Hip Abduction Test (AHA) is an assessment of lumbopelvic control during performance of a low-demand functional lower extremity activity.[111] The test requires an individual to maintain neutral lumbopelvic alignment in an unstable position, while actively abducting the hip/ lower extremity. An ordinal scale from 0 to 3 is used to quantify the amount of frontal plane control ("0" for no loss of frontal plane position, "3" for severe loss of frontal plane position) of the lumbopelvic complex during performance of the AHA.[111] Poor performance on the AHA predicted the development of low back pain in prolonged standing in previously asymptomatic individuals (OR: 3.85, 95% CI: 1.05-19.07).[111]

Figure 5. The Active Hip Abduction Test (AHA). Athletes assume a side-lying position and must maintain neutral spine and pelvis alignment while raising the top leg.

The single-leg hop for distance (SLH) is commonly used to assess lower extremity function and neuromuscular control in athletes following ACL reconstruction.[112,113] The SLH is similar to a myriad of functional movements often seen in sports, such as running and jumping. The test requires an athlete to stand in single-leg stance, jump forward a maximum distance, and land in single-leg stance (on the same stance leg) while maintaining balance and control on the landing. Female collegiate athletes with a side-to-side asymmetry greater than 10% were 4 times more likely to sustain a foot or ankle injury (OR: 4.4, 95%CI: 1.2-15.4, p = 0.02) while their male counterparts who hopped more than 75% of their respective heights were at least 3 times more likely to sustain a low back or lower extremity injury (OR: 3.6, 95% CI: 1.2-11.2, p = 0.03).[77]

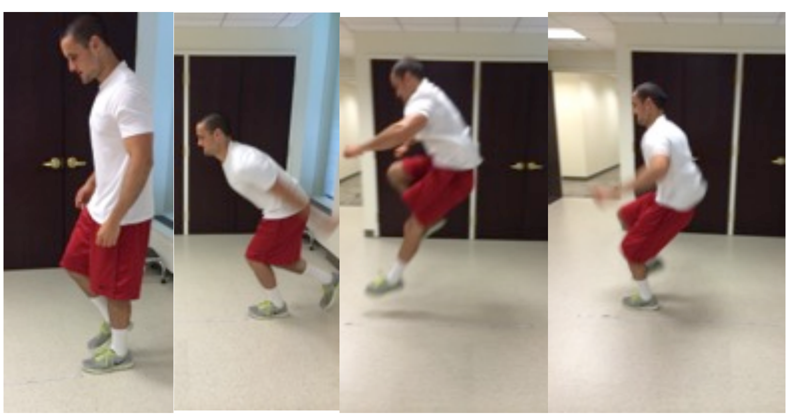


Figure 6. The Single-leg hop test (SLH). Athletes assume a single-leg stance, hop forward as far as possible, and land on same leg in single-leg stance. The distance hopped is measured from the start line to the heel of the stance leg at landing.

Summary of Limitations of the Current Clinical Tests or Screens

First, an important limitation of the FMS is that 4 of the 7 tests assess lower extremity movement patterns, and there is lack of clear indication of an independent core stability assessment, in terms of both muscle capacity (strength and endurance) and neuromuscular control. Taking a movement system approach, based on Kibler's kinetic chain theory, emphasizes the demand for core stability assessment, as the core is the link between the upper and lower extremities for energy transfer. Although it is assumed that core stability is required to efficiently perform the FMS, neuromuscular control within other regions also affect performance. Therefore, without an independent core stability test, it may be difficult to determine whether poor performance is a result of poor core stability. To date, there are no clinical assessments of core stability, specifically neuromuscular control, that have been validated against a "gold standard" or appropriate lab-based measures. My preliminary studies 3 and 4 were designed as a means of assessing the validity of currently used clinical tests of core stability and a potential test I developed as clinical assessment that focuses on the neuromuscular control aspect of core stability.

Second, only one test within the FMS and 16-PPM is suggested to directly assess upper extremity movement patterns, which limits the screen's ability to fully assess upper extremity performance and symmetry. The AAA does not include any assessment of upper extremity movement patterns, however, it does assess upper extremity muscle capacity.

Third, there is conflicting evidence in the literature of the ability of established pre-participation screens, such as the FMS, 16-PPM, and AAA, to predict injury in athletes and military personnel. FMS composite scores less than or equal to 14 have been suggested to predict injury, however, published normative values in healthy middle-aged adults reveals an average composite score of 14.2 ± 2.9, while the average composite score in athletic populations has been reported as low as 14.3 ± 1.8.[50,98] The lack of variance in the scores among clearly different populations of individuals may be due to a testing and/or scoring structure that does not effectively discriminate performance of general athletic skills or tasks. This may affect the ability of the screen to distinguish levels of athletic performance or identify risk of injury due to performance degradations. To date, there is no evidence to suggest the 16-PPM or AAA has injury predictive capabilities.

Fourth, there is a clear need to develop and test the psychometric properties of a pre-participation screening tool to assess the movement system in terms of the efficiency, movement patterns of the upper and lower extremities, and regional stability. The screen should utilize both static and dynamic tests to potentially identify impairments or compensations in the kinetic chain under different conditions and challenges. Performance degradations may be identified in either static or dynamic tests, or possibly both, which in turn may influence further analysis and/or interventions. Tests should be designed as progressively challenging in an effort to identify an individual's preferred movement pattern or motor control strategy and potentially discriminate between individuals with excellent, good, and poor performance.

PRELIMINARY STUDIES

Preliminary work to date has focused on identifying gaps in current injury risk assessments in athletes, identifying and/or developing screening tests that address the gaps in current screens, establishing the theoretical constructs, determining preliminary inter-rater reliability of the newly developed tool and preliminarily examining the relationship of selected clinical core stability tests to lab-based measures of core stability.[114]

Preliminary Study 1: Identification and development of potential screening assessments

Relevant Specific Aim: 1A) Utilizing the current literature and an expert panel, identify clinical tests that demonstrate evidence of injury prediction in athletes for the core, upper and lower extremity and select a comprehensive subset of tests.

An extensive literature search was performed to identify current athletic injury clinical screening assessments as well as upper and lower extremity movement pattern assessments. Any assessments that were utilized in an athletic population as part of a clinical pre-participation screen for injury risk were included. Prospective studies that assessed the ability of the screen to predict injury were considered important. An extensive literature search was then conducted to identify common clinical tests of core stability, as this is a proposed risk factor for injury. Once these screens were identified, a panel of experienced Physical Therapists (Refer to Appendix 2 for details) was consulted to discuss the evidence and any possible assessments that are used in practice that may have not presented in the literature search.

The search returned several injury predictive assessments: the FMS, Y-Balance Test, CKCUEST, GIRD, and the SLH.[77,87,102,105,108] The Active Hip Abduction test was included as it demonstrated ability to predict low back pain in asymptomatic adults.[111] Upper and lower extremity movement pattern assessments included the scapular dyskinesis test, single-leg step down, and single-leg hop.[17,78,115] Scapular dyskinesis was included to assess upper extremity movement efficiency and control. Injury, muscle weakness, or muscle inflexibility can affect scapular alignment statically and dynamically, potentially altering scapulohumeral rhythm and humeral positioning during dynamic movements.[116] The single-leg step down was included due to its common use as an assessment of hip muscle function and lower extremity neuromuscular control.[78] Common core stability assessments included the sustained side bridge, trunk extensor endurance, trunk flexor endurance, and double-leg lowering test.[4,24,81] Discussion with an expert panel generated a larger list of assessments that are commonly used to assess core stability and/or control as well as muscle length/flexibility. The panel thought that assessment of movement patterns in more dynamic situations and flexibility of key muscle groups were necessary as either key factors or to assist in interpretation of other assessment findings. For example, the Modified Thomas Test was added in an effort to ensure deviations observed during the prone hip extension test were not due to anterior hip tightness. Thus, altered performance on the prone hip extension could be considered a result of an altered control mechanism.

Additional proposed assessments included single-joint and multi-joint assessments such as the prone single-leg hip extension, prone hip extension with contralateral arm lift. The hip extension test was included to assess lumbopelvic control during an isolate single-joint movement. The hip extension with contralateral arm lift was included because the activation of the latissumus dorsi (via the arm lift) coupled with the activation of the gluteus maximus (via hip extension) is theorized to contract the thoracolumbar fascia and provide stabilization to the lumbar spine via compression.[117,118] Altered movement patterns within the progression from hip extension with contralateral arm lift to hip extension may suggest impaired lumbopelvic neuromuscular control.

With the goal of developing a comprehensive performance-based movement system-screening tool, the above-mentioned tests were then combined to form the skeleton of a novel assessment. The FMS (all tests), YBT, AHA, GIRD, CKCUEST and SLH tests were included because of their demonstrated injury predictive capabilities, as well as their ability to assess asymmetry between sides. The remaining tests were included because of their suggested ability to assess core stability, flexibility of the anterior hip, upper extremity range of motion and movement patterns, and dynamic unilateral lower extremity movement patterns.

Sports such as baseball, lacrosse, tennis, soccer, volleyball and basketball rely on trunk control in all 3 planes of movement. Athletic screening tools should address this demand. Frontal and transverse plane challenges are not well represented in the FMS. The 16-PPM and AAA include more frontal plane challenges than the FMS, however, transverse plane assessment may be under represented. In an effort to challenge lumbopelvic control in these planes, I decided to incorporate progressions (such as adding manual resistance) to individual tests that were suggested to assess control. The progressions were designed to increase the challenge on the system, potentially allowing for the identification of breakdowns at varying degrees of demand (i.e. static vs. dynamic or loaded vs. unloaded). This will possibly aid in identifying compensations or altered movement patterns within the kinetic chain. While the FMS relies heavily on assessing lower extremity movement patterns, it lacks assessment of muscle performance or capacity in the upper and lower extremity and core. Therefore, tests designed to assess both static and dynamic performance (i.e. endurance tests and hop tests) were included to address this limitation.

The procedures for each test were developed based on published protocols, when available, and were then evaluated for common deviations from the expected performance. These deviations were considered as important qualitative information that could be used to identify potential breakdowns within the kinetic chain. Because many of the tests included in the new comprehensive screen had different quantitative scoring mechanisms, we decided to only record qualitative deviations from the expected performance of the test. This allows the clinician to focus their attention solely on assessing the quality of the movement during each test without having to recall a variety of different scoring procedures. The data collection sheet (see Appendix 3) includes check boxes for pain, region of deviation (i.e. knee, hip, ankle), amount of deviation (i.e. none, subtle, obvious), and symmetry.

The new screening tool is designed so that movements with similar patterns are done in a progressive and systematic nature. Progressions are designed to increase the challenge on the pattern or control mechanism being assessed, unlike previously documented screens. The series are as follows: side-lying series, supine series, bridge series, prone/quadruped series, bridge series, upper extremity, and dynamic series. A schema detailing the type of test (flexibility, muscle performance, neuromuscular control), whether the test is static or dynamic, and body region being assessed is available in Appendix 4. This served as the initial screening tool for further preliminary work.

Relevance to my proposed research: This study provided an initial comprehensive performance-based movement system-screening tool consisting of 32 tests, with face validity, instructions for testing, and rater training manual.

Study 2: Relationship between FMS, YBT, and lab-based measures of core stability

Relevant Specific Aim: 2A) Determine criterion validity of the clinical tests of core stability by validating the clinical core screening items within the comprehensive performance based movement system screen against lab-based measures of core stability.

How well common pre-participation screens with injury predictive capabilities assess aspects of core stability has not been established. In order to develop a comprehensive performance-based movement system-screening tool, it is necessary to identify and understand the constructs that previously identified assessments are based upon. While certain constructs, such as core stability, are theorized to be required for optimal performance of functional movement, the extent to which core stability is measured by functional movement is unknown. The purpose of this preliminary study was to determine relationships between currently established screening tools of functional movement patterns (FMS), a dynamic single leg balancing (YBT) and biomechanical measures of isolated core stability with emphasis on neuromuscular control. Twelve healthy recreational athletes (5 males, mean age: 25.3 ± 4.1 years) completed the FMS, YBT, and a biomechanical test of isolated neuromuscular core stability (Figure 13 and protocol in Apendix 5). To reduce contribution from the lower extremities, isolated core stability was tested using an unstable chair situated on an elevated force platform. Three 60s balance trials, where the subject was asked to move as little as possible with their eyes closed, were used to assess core stability. Center of Pressure (COP) data were quantified using the 95% Confidence Ellipse Area (CEA) (CEA, mm^2) and average displacement of the COP per second (MVEL) (mm/s). For the biomechanical measures of core stability, higher values represent less control of position and velocity. Pearson's (r) or Spearmans rho (r_s) correlations were used to assess relationships between biomechanical measures of core control, FMS total score (0-21), and normalized YBT reach distances (% leg length). P<0.1 was considered an important trend. There was a significant moderate correlation between FMS and MVEL r_s (7) = -.66, p = .05, YBT ANT and CEA r (7) = -.60, p = .09, and YBT ANT and MVEL r (7) = -.72, p = .03. FMS and CEA, YBT MED, and YBT LAT demonstrated no correlation with biomechanical core stability measures (Table 2).

Table 2. Correlation between FMS, YBT, and lab-based isolated core stability.

	CEA	**MVEL**	***FMS**	****YANT**	****YMED**
CEA (mm^2)					
MVEL (mm/s)	**0.82**				
*FMS (0-21)	-0.32	**-0.64**			
**YBT ANT (%LL)	-0.43	**-0.68**	**0.72**		
**YBT MED (%LL)	**-0.52**	**-0.74**	**0.44**	**0.56**	
**YBT LAT (%LL)	-0.13	-0.43	0.38	0.22	**0.83**

Abbreviations: EC_CEA: Eyes Closed 95% Confidence Ellipse Area of the CoP; EC_MVEL: Eyes Closed Mean Velocity of CoP; FMS: Functional Movement Screen; YBT_ANT: Y-Balance Test Anterior Reach; YBT_PM: Y-Balance Test Posteromedial Reach; YBT_PL: Y-Balance Test Posterolateral Reach.

This data suggest that core stability accounts for up to one third of the variance in the FMS (37%) and up to half of the variance in the YBT ANT (36-52%). Thus, core stability is a sizeable component of each test, but other factors not tested here have a large impact on test scores. While core stability may be an underlying construct within the FMS and YBT, these tests were not designed to as independent core stability assessments.

Relevance to my proposed research: The results from this study support the need for development of a clinical test(s) of core stability to include as components of a comprehensive screening tool.

Study 3: Relationship between clinical tests and lab-based measures of core stability

Relevant Specific Aim: 1B) Describe newly developed tests of clinical core neuromuscular control and core muscle capacity.

Most clinical measures of core stability have not been validated, and the use of biomechanical measures to study clinical tests of core stability is limited. The objective of this preliminary study was to determine the criterion validity of two novel clinical core stability tests, as well as the relationship between common clinical core stability tests. The goal was to determine the potential value of these tests for inclusion into the MSST.

The novel tests include the trunk stability test (TST) (Fig 9 below) described by Noehren et al [119], which was modeled as a clinical version of the seated biomechanical lab based measure and the unilateral hip bridge endurance test (UHBE).[120] The lab measure protocol has been previously used as a valid and reliable test to assess differences in trunk control.[27] Interpretation of findings in a recent study suggests that of the TST can detect trunk neuromuscular control impairments in an ACL rehabilitation population.[119] Evidence suggests the unilateral hip bridge requires significant activation of the lumbar stabilizers.[121] This test was performed as an endurance test (UHBE) in an effort to assess the capacity and neuromuscular control of the lumbopelvic complex. The novel tests were also compared to common clinical measures of core stability and postural control. These tests included the trunk extensor endurance (TEE) and Y-Balance Test (YBT). We hypothesized that the TST and UHBE would demonstrate a moderate correlation to the lab-based biomechanical measure of isolated core stability.

Twenty healthy recreationally active individuals (11 males; age 23.5+/-1.7 years; height 173.0+/-8.3 cm; weight 71.9+/-15.5 kg) completed a lab-based measure of core stability and a battery of clinical tests that as associated with assessment of core stability: UHBE (s), YBT (reach as % leg length), TST (errors), (TEE) (s).

Figure 7. Unilateral Hip Bridge (UHBE). Athletes must maintain a neutral spine and pelvis while in a single-leg bridge position. A digital inclinometer around the waist displays the amount of movement in the transverse plane.

Figure 8. Trunk Extensor Endurance (TEE). Athletes are secured to a mat table using mobilization belts at the buttocks, thigh, and ankle. Athletes must maintain a neutral spine position (as shown) maximum time. The test is terminated once a 10-degree change in position in noted.

Figure 9. Trunk Stability Test (TST). Athletes must maintain balance on a standard Swiss ball (75cm) with one foot on the ground, arms across the chest, and eyes closed. The number of errors is recorded during three-30s trials on each foot.

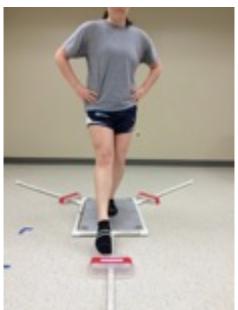


Figure 10. Y-Balance Test (YBT_ANT). Athletes assume a single-leg stance and are required to push a box as far as possible in front of them with the non-stance leg. The distance (cm) the box is pushed is recorded for three trials, averaged, and then normalized to leg length.

The UHBE was performed with the subject lying supine with the arms crossed, the knees at 90 degrees, and the feet flat on the table. The subject performed a double-leg hip bridge. Once a neutral spine and pelvis were achieved, the subject was instructed to extend their left knee so that their left leg was straight and their thighs parallel to one another. Subjects were instructed to hold this neutral/start position as long as possible. Pelvic positioning was determined by a digital inclinometer attached to a belt that was tightly secured to the individual's pelvis with contact at both ASIS. This is a timed test with the number of seconds a subject was able to hold the position (maintain a neutral spine or pelvic positioning as noted by less than 10-degree change in alignment) recorded.

The TST was performed with the subject sitting on a Swiss ball (75cm), one foot lifted from the ground, eyes closed, and attempting to balance for 30s. Errors were recorded and included: plant foot moving, uncrossing the arms, elevated foot touches ground, eyes open, reaching for the table, and time out of test position. Control of seated balance during the TST was observed by a trained clinician and scored based on control errors.[119] TEE was tested using the modified Sorenson position in which they were strapped to a table using mobilization belts at the buttocks, knee, and ankle. Subjects were instructed to cross their arms and keep their torso parallel to the floor for as long as possible. An inclinometer was placed between the shoulder blades to determine any change in position. The test was terminated when the subject requested to stop or when a 10-degree change in alignment was noted, whichever came first. The test was completed 2 times with ability to maintain control of position recorded in seconds. YBT was assessed as per Pilsky et al, 2009.[122] Performance of this screening test is detailed in the MSST Manual (Appendix 6).

Biomechanical isolated core stability was tested using the seated paradigm from preliminary study 2 (see Appendix 5). Test trials were averaged. Spearman's rho and Pearson's correlations were used, as appropriate, to determine the association between measures. Correlations were interpreted according to Cohen (<0.1: trivial, 0.1-0.3: small, 0.31-0.5: medium, >0.5: large).[123]

Mean (SD) values for the clinical measures can be found in Table 3 below.

Table 3. Performance statistics for biomechanical and clinical tests.

Variable	Mean ± SD	Range (Min-Max)
EC_CEA (mm^2)	344.6 ± 276.5	94.2 - 1063.9
EC_MVEL (mm/s)	10.4 ± 5.1	4.6 - 23.8
L_TST (errors)	5.1 ± 4.0	0.0 - 14.0
R_TST (errors)	6.5 ± 3.9	0.3 - 16.3
UHBE (s)	23.0 ± 16.5	3.1 - 59.5
TEE (s)	78.6 ± 24.2	43.3 - 120.7
YBT_ANT (%LL)	81.7 ± 6.3	68.5 - 95.7
YBT_PM (%LL)	96.1 ± 8.2	74.2 - 114.3
YBT_PL (%LL)	90.3 ± 7.7	76.3 - 106.7

Abbreviations: EC_CEA: Eyes Closed 95% Confidence Ellipse Area of the CoP; EC_MVEL: Eyes Closed Mean Velocity of CoP; L_TST: Left Foot planted Trunk Stability Test; R_TST: Right Foot planted Trunk Stability Test; UHBE: Unilateral Hip Bridge Endurance; TEE: Trunk Extensor Endurance; YBT_ANT: Y-Balance Test Anterior Reach; YBT_PM: Y-Balance Test Posteromedial Reach; YBT_PL: Y-Balance Test Posterolateral Reach.

Means for YBT and TEE were similar to previously reported means. TST means were slightly higher than previously reported, [119] however the current study did not use competitive athletes. There was little to no correlation between TST and biomechanical measures of core stability (rho = 0.2 – 0.22), thus it appears they are testing different aspects or regions of control. Results can be found in Table 4a and 4b below.

Table 4a. Relationship between the novel clinical tests of core stability and biomechanical measure of core stability.

	EC CEA	EC MVEL
L TST	0.02 (0.46)	-0.14 (0.27)
R TST	0.22 (0.18)	0.06 (0.41)
UHBE⌘	***-0.49 (0.01)***	***-0.56 (0.01)***

Data represent Spearman's rho value (p value).
Abbreviations: EC_CEA: Eyes Closed 95% Confidence Ellipse Area of the CoP; EC_MVEL: Eyes Closed Mean Velocity of CoP; L_TST: Left Foot planted Trunk Stability Test; R_TST; Right Foot planted Trunk Stability Test; UHBE: Unilateral Hip Bridge Endurance.
Bold italics $p \leq 0.05$
⌘ represents combined sides

Table 4b. Relationships between different clinical measures of core stability.

	TEE	YBT ANT⌘	YBT PM⌘	YBT PL⌘
L_TST	-0.18 (0.22)	-0.09 (0.36)	***-0.41 (0.04)***	***-0.42 (0.03)***
R_TST	-0.24 (0.16)	-0.08 (0.37)	-0.35 (0.06)	***-0.43 (0.03)***
UHBE⌘	0.27 (0.12)	0.05 (0.42)	-0.08 (0.37)	-0.27 (0.12)

Data represent Pearson's r value (p value).
Abbreviations: L_TST: Left Foot planted Trunk Stability Test; R_TST: Right Foot planted Trunk Stability Test; UHBE: Unilateral Hip Bridge Endurance; TEE: Trunk Extensor Endurance; YBT_ANT: Y-Balance Test Anterior Reach; YBT_PM: Y-Balance Test Posteromedial Reach; YBT_PL: Y-Balance Test Posterolateral Reach
⌘ represents combined sides
Bold italics: $p \leq 0.05$

The data suggest that the isolated core stability explains 24-31% of the variance in the UHBE. As both the UHBE and biomechanical measure of core stability demand control of the lumbo-pelvic region to maintain the testing position, the moderate relationship between these tests preliminarily supports the utility of the UHBE as a clinical test of core stability. There was not a significant relationship between the TST and our lab-based biomechanical measures. This data suggest that the TST is moderately correlated to dynamic unilateral postural control, as tested by the YBT, but not core stability. This evidence supports the use of the UHBE as a clinical core stability test; however, further work is needed to develop or determine if other clinical tests can assess the neuromuscular control aspect of core stability. Even though the novel clinical test (TST) was not correlated with the biomechanical measure, the TST demonstrated a significant moderate relationship to dynamic unilateral postural control as evaluated by the YBT.

A secondary analysis of the location of the errors recorded in the TST revealed that approximately 85% of the errors were linked to lower extremity (LE) movements (such as the plant foot moving), while 11% were related to the trunk or upper extremity motion (such as the arms uncrossing or reaching for the table). This may suggest that the TST captures LE control (via the leg in contact with the floor), or perhaps more of a LE control strategy, rather than trunk control or core stability, however, further research is needed to understand this relationship.

Relevance to my proposed research: The results of this study preliminarily support the utility of the novel UHBE and TEE as measures of core neuromuscular control and muscular capacity within a comprehensive pre-participation screen. The UHBE assesses control of the lumbopelvic complex in sagittal and transverse planes, while the TEE measures the capacity of the trunk extensors. These tests should be used in conjunction with measures that assess control in the frontal plane in an effort to capture information regarding core stability in all planes of motion. Based on these findings, the UHBE was added to the modified (version 2) of the screen.

Study 4: Inter-Rater Reliability of Items with the comprehensive performance-based movement system screening tool MSST

Relevant Specific Aim: 2B) Determine screen constructs and inter-rater reliability of tests within the comprehensive performance-based movement system screen.

As an initial version (version 1) of the screen was developed, an expert panel preliminarily assessed the screen's constructs. For a detailed schema of the screen constructs and testing procedures, please refer to the MSST Manual in Appendix 6. Preliminary inter-rater reliability of individual items or tests within the newly developed comprehensive screen was assessed in two different preliminary studies. In the first study, inter-rater reliability was assessed between a primary and secondary rater in a cohort of freshman female college dance majors (N=22, mean age: 18.1 ± 0.74, height: 161.3 ± 5.5 cm, weight: 57.6 ± 8.4 kg). Raters were trained in a single session where raters watched a training video, followed by a detailed discussion of each test and scoring procedure, and concluded with a practice scoring session. The training session lasted approximately 4 hours and was conducted by the developers of the screen (physical therapists and a strength and conditioning specialist). Raters included Physical Therapists, physical therapy students, certified strength and conditioning specialists, and biomechanists. In the practice scoring session, raters viewed a training video, independently scored the video, and then discussed their scores as a group. Raters were also given access to the screening tool manual and training video for future reference or study. Raters were then randomly assigned to a station for the screening protocol of the dancers. Each station consisted of one of the series within the screen and lasted approximately 5 minutes. The primary rater was responsible for all instructions to the subject. Raters scored each test independently. A single rater was used for all upper extremity tests because he had significant prior experience with rating these tests as well as excellent intra-rater reliability. Kappa was used to assess inter-rater reliability and interpreted according to Landis and Koch.[124,125] Results are located in Tables 5a-5d.

Inter-rater agreement ranged from slight (0.06) to excellent (1.00) in this cohort of college dancer majors. Agreement was based on whether or not each rater observed a fault/deviation from the expected performance of the task and did not depend on the amount of the deviation or where each rater marked the deviation. The active hip abduction, active hip abduction with resistance, and hip bridge with lower extremity extension demonstrated the poorest agreement bilaterally, while some tests displayed moderate to substantial agreement on one side and poor to slight on the other side. The wide range of agreement between raters could be a result of inadequate training of the raters and/or differences in experience levels among raters.

The second preliminary study assessed inter-rater reliability between two trained raters (one experienced PT and one of the screen developers) in a cohort of varsity collegiate athletes (N=15). Subjects were Division I collegiate athletes (8 females; mean age = 22.8 ± 4.3, height = 174.8 ± 11.2 cm, weight = 77.9 ± 17.8 kg). Both raters were involved in the first study with the dancer cohort and were trained as per the protocol manual. The primary rater was responsible for all instructions to the subjects, however; each rater observed and scored each test independently. Measurement, range of motion, and timed tests were not scored by multiple raters. Rather, the raters agreed that the test was performed correctly and that the recorded score/measurement was accurate. The same statistical procedures and interpretation were used as the previously mentioned inter-rater reliability study. Results are located in Tables 5a-5d below. Kappa values were averaged for tests with bilateral scores. Kappa values for individual sides can be found in Appendix 7.

Table 5a. Lower extremity/trunk mobility and symmetry test inter-rater reliability.

Test	Type	Region	Dancer κ	Athlete κ	Published Reliability
Modified Thomas test (MTT)	MOB/SYM	LE	0.42	*NV	κ=0.47 (Peeler, 1997); ICC=0.9 (Gabbe et al 2004)
Active straight leg raise (ASLR)	MOB/SYM	LE	*NV	*NV	κ=0.88 (Onate et al 2012)
Flexion clearing test (FLEX)	MOB/SYM	Trunk/Pelvis	*NV	*NV	None reported
Extension clearing test (EXT)	MOB/SYM	Trunk/Pelvis	*NV	*NV	None reported
Shoulder clearing test (SHO CLR)	MOB/SYM	UE	NA$^{\infty}$	*NV	None reported
Shoulder mobility (SHO MOB)	MOB/SYM	UE	NA$^{\infty}$	NA$^{\infty}$	κ=0.90 (Onate et al 2012)
Glenohumeral internal rotation deficit (GIRD)	MOB/SYM	UE	NA$^{\infty}$	NA$^{\infty}$	ICC=0.77 (Kevern et al 2014).

Abbreviations: MOB: mobility; SYM: symmetry; DYN: dynamic; LE: lower extremity; UE: upper extremity; NA: not applicable; *NV: no between subject variance; κ: kappa; ICC; intraclass correlation coefficient.
∞ denotes not applicable because scored by only one rater.

Table 5b. Lower extremity/hip muscle performance test inter-rater reliability.

Test	Type	Region	Dancer κ	Athlete κ	Published Reliability
Active hip abduction (AHA)	MP	LE/Hip	0.26	0.46	ICC=0.59-0.70 (Davis et al 2011)
Active hip abduction resisted (AHAR)	MP	LE/Hip	0.06	0.61	None reported

Abbreviations: MP: muscle performance; DYN: dynamic; LE: lower extremity; κ: kappa; ICC; intraclass correlation coefficient.

Table 5c. Trunk/pelvis neuromuscular control test inter-rater reliability.

Test	Type	Region	Dancer κ	Athlete κ	Published Reliability
Double-leg lowering test (DLLT)	NMC	Trunk/Pelvis	NT	*NV	None reported
Side bridge (SB)	NMC	Trunk/Pelvis	0.40	*NV	ICC=0.99 (McGill, 1999)
Side bridge w/ hip abduction (SBA)	NMC	Trunk/Pelvis	0.41	0.17	None reported
Side bridge w/ hip abduction resisted (SBAR)	NMC	Trunk/Pelvis	0.34	0.54	None reported
Bilateral hip bridge (HB)	NMC	Trunk/Pelvis	0.21	*NV	None reported
Unilateral hip bridge (UHB)	NMC	Trunk/Pelvis	0.15	0.49	None reported
Unilateral hip bridge resisted (UHBR)	NMC	Trunk/Pelvis	*NV	*NV	None reported
Prone hip extension (HE)	NMC	Trunk/Pelvis	0.82	0.81	κ=0.72 (Murphy et al 2006)
Rotary Stability (RS)	NMC	Pelvis	*NV	*NV	*NV (Onate et al 2012)
Hip extension with contralateral arm lift (HEUE)	NMC	Trunk/Pelvis	0.36	0.27	None reported

Abbreviations: MOB: mobility; NMC: neuromuscular control; DYN: dynamic; NA: not applicable; NT: not tested; NV: no between subject variance; κ: kappa; ICC; intraclass correlation coefficient.
∞ denotes not applicable because scored by only one rater.

Table 5d. Trunk/pelvis/LE/UE neuromuscular control test inter-rater reliability.

Test	Type	Region	Dancer κ	Athlete κ	Published Reliability
Trunk stability push-up (PUSH)	NMC	Trunk/Pelvis	0.81	*NV	κ=0.75 (Onate et al 2012)
Squat (SQUAT)	NMC	Trunk/Pelvis /LE	0.46	*NV	κ=1.00 (Onate et al 2012)
Hurdle step (HURDLE)	NMC	Trunk/Pelvis /LE	0.49	0.94	κ=0.33 (Onate et al 2012)
In-line lunge (LUNGE)	NMC	Trunk/Pelvis /LE	0.32	*NV	κ=0.88 (Onate et al 2012)
Scapular dyskinesis (SCAP DYS)	NMC	UE	NA	NA$^{\infty}$	κ_{ω}=0.48-0.61 (McClure et al 2009)
Step down (STEP)	NMC	Pelvis/LE	*NV	0.58	ICC=0.94 (Loudon et al 2002)
Y-Balance Anterior (YBT)	NMC	Pelvis/LE	NA$^{\infty}$	NA$^{\infty}$	ICC=0.86-0.92 (Gribble et al 2013)
Single leg hop (SLH)	NMC	Pelvis/LE	NA$^{\infty}$	NA$^{\infty}$	ICC-0.84-0.87 (Johnsen et al 2015)

Abbreviations: MOB: mobility; NMC: neuromuscular control; DYN: dynamic; LE: lower extremity; UE: upper extremity; NA: not applicable; *NV: no between subject variance; κ: kappa; ICC; intraclass correlation coefficient.
∞ denotes not applicable because scored by only one rater.

Inter-rater reliability in this cohort of collegiate athletes ranged from slight (0.03) to perfect (1.00) agreement, similar to previous results in the cohort of college dance majors. Overall, the agreement was markedly higher in the athletic cohort, with only two tests demonstrating slight agreement (left hip extension with upper extremity lift and left side bridge with abduction). Outside of those two tests, rater agreement ranged from 0.25 to 1.00, fair to perfect. The three tests that demonstrated the poorest agreement bilaterally (AHA, AHAR, and HBEXT) in the previous study demonstrated better agreement overall in the athlete study, possibly supporting the need for an increase in the quality and quantity of rater training prior to testing. The results of the athlete produced inter-rater reliability are similar to published reliability of the FMS items; however, AHA and step-down reliability was notably lower in the current study. One explanation for the lower inter-rater agreement could be that the "scoring" mechanisms used in the current study were different than the published protocols. Future work should evaluate the rater training procedure for improved reliability as well as the training manual and test instructions for improved efficacy.

Relevance to my proposal research: This study provided a preliminary version of the screen, an evaluation of inter-rater reliability of individual test items within the MSST, and provided guidance to my hypotheses. This study also provided a preliminary assessment of which items in the screen potentially have poor inter-rater reliability and will thus be omitted from the next draft of the screen. This study aided the decision to refine test explanations and instructions within the MSST protocol manual, add more in-depth training, as well as more overall time in rater training.

Study 5: Development of a Novel Clinical Assessment of Core Stability

With a majority of the errors in the TST reported as lower extremity movements or adjustments (preliminary study 3), we developed a new clinical test designed to assess core neuromuscular control while removing any influence from lower extremity contact with the ground. Based on above finds of the TST, we decided to develop a new clinical test that might better assess isolated core control. The Core Control Clinical Test (CCCT) was developed as a clinical version of the biomechanical measure of isolated core neuromuscular control used in the current study.

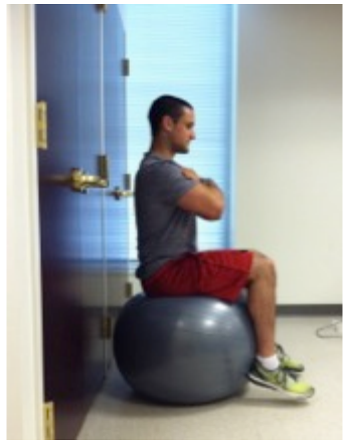


Figure 11. Clinical Core Control Test. This test requires an individual to maintain an upright posture with the feet removed from the ground, the arms across the chest and calves and heels in contact with the ball for as long as possible.

The CCCT requires the individual to maintain an upright trunk position with the arms across the chest, while sitting on a Swiss ball with their feet off the ground and calves and heels in contact with the front of the Swiss ball. Individuals are given a familiarization period followed by two recorded trials for maximum time in position as per the protocol (Appendix 8). This test is assessed by recording the length of time the subject is able to maintain an upright posture without the feet touching the ground or the ball touching the wall behind them. The recorded trials are complete when a foot touches the ground or the ball touches the wall (located 6 inches behind them). Through observation of performance it is clear that this test requires lumbo-pelvic-hip complex control to maintain the position of the trunk in relation to the pelvis and ball. Primary adjustments are made using the musculature of the lumbo-pelvic-hip complex as opposed to the weight bearing lower extremity, as seen in the TST. Spearman's rho correlations were used to assess the relationship between the seated paradigm used in preliminary study 2 and CCCT. Preliminary data (N=16) on varsity athletes and healthy adults suggests a significant moderate association between CCCT and EC_CEA and EC_MVEL $r_s = -0.47$ ($p=0.03$), representing 22% of the variance explained. This data suggest that while core neuromuscular control may explain 22% of the variance within the CCCT, other factors not tested here may influence performance. This evidence preliminarily supports the use of the CCCT as clinical test of core neuromuscular control; however, further work should be done to determine the utility of the CCCT as a clinical test of core stability within a battery of core stability tests that include both muscle capacity and neuromuscular control. The addition of the CCCT to the comprehensive screening tool will potentially provide a measure of core control in all three planes of motion. If the relationship between the CCCT and the lab-measure endures, this test will be the primary test within the screen that assesses neuromuscular control of the lumbo-pelvic-hip complex in three dimensions. If this relationship persists, it may support the utility of this test as a clinical measure of core control and may be used in combination with a core muscle capacity test, such as the TEE or UHBE, to assess all facets of core stability.

The preliminary work thus has provided an initial set of clinical tests that can be used as part of a comprehensive pre-participation screen, while addressing gaps and/or limitations in currently documented screens. The work has also resulted in preliminary understanding of the role of core stability in a few common clinical assessments. All novel assessment protocols were discussed in detail with experts within the field of human movement (physical therapists, athletic trainers, and biomechanists) and based on preliminary data were included in a modified version of the screen. Based on this initial version of the screen, we preliminarily assessed inter-rater reliability within the new comprehensive screen.

Relevance to my proposal research: The results of this study provide preliminary evidence to the support the utility of a novel clinical assessment of core neuromuscular control in athletes. The items were added to the pre-participation screening tool and will be validated against the lab-based biomechanical measure of isolate core stability in a larger sample focused to athletes.

RESEARCH DESIGN AND METHODS

Research Design

The purpose of the proposed research is to develop and begin validation of the MSST for utility as an assessment of performance and potential injury risk in athletes. The steps involved in developing and validating the tool (MSST) are: (1) identifying a conceptual framework and model for the assessment; (2) utilizing current evidence and an expert panel of sports medicine professionals to assist in developing the assessment; (3) pilot testing the initial screen; (4) modifying the initial screen based on preliminary work; (5) distributing the modified screen to an expert panel for additional review; (6) developing a quantitative scoring system for the screen; (7) determining selected psychometric properties of the screen; (8) modify the screen based on psychometric properties and expert review; and (9) preliminarily determining the screen's ability to discriminate between athletes with and without non-traumatic shoulder injury. The first three steps were accomplished with the preliminary studies. Specific Aim 1 in the dissertation will accomplish the fourth, fifth, and sixth steps. Aim 2 will accomplish steps seven and eight, while Aim 3 will accomplish the final step.

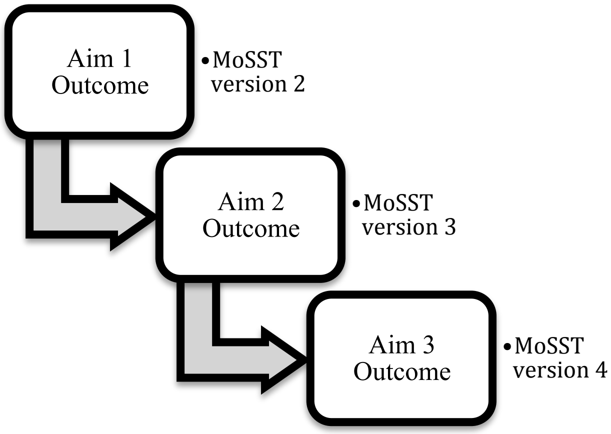


Figure 12. Schematic outlining the evolution of the MSST based on completion of specific aims.

Specific Aim 1: Describe a comprehensive performance-based movement system screening tool for athletes.

1A) Utilizing the current literature and an expert panel, identify clinical tests that demonstrate evidence of injury prediction in athletes for the core, upper and lower extremity and select a comprehensive subset of tests.

1B) Describe newly developed tests of clinical core stability.

This study will accomplish the fourth, fifth, and sixth steps in the development of the MSST. Items with injury predictive capabilities selected from the current literature of upper and lower extremity and core stability evidence and newly developed tests will produce an initial comprehensive set of performance-based clinical assessments that can be used for screening in an athletic population. This study will utilize an expert panel of experienced Physical Therapists with sports and orthopedic specialty certifications, Athletic Trainers, certified strength and conditioning specialists, and biomechanists from Drexel University, University of Pennsylvania, Marquette University, and The Ohio State

University to assess the *content validity* of the initial comprehensive set of clinical assessments of movement pattern performance, upper and lower extremity screens, and core stability measures. Experts were chosen based on their experience and knowledge in orthopedic assessment. Physical Therapists with Orthopedic Specialist Certification or with Sports Specialist Certification were chosen because of their specific skills and training in assessing human movement. The list of assessments that was generated during the initial literature search, preliminary work in test item development and initial round of expert panel review will be used to further modify the screen. This modified screen will be given back to the expert panel and assessed for the agreement related to the following:

1. Each item's determination of testing construct: movement pattern efficiency, stability, and/or mobility.

2. Each item's determination of level of current evidence-based support or pragmatic use in the clinic as a screening tool for performance and/or risk factor of injury.

3. Each item's body region or regions of assessment core stability (either neuromuscular control or capacity), upper extremity, or lower extremity functional movement patterns or symmetry.

4. Each item's proposed list of deviations from the expected optimum performance of the test.

5. The initial proposed scoring system based on current evidence, item performance expectations, and distribution of selected constructs.

6. Level of inter-rater agreement and test redundancy required for further modification.

The panel's opinions will be objectively assessed via a modified Delphi technique using Drexel Qualtrics. An initial round of informal consensus was completed in preliminary study 1. For round 2, experts will be asked to rate their level of agreement on the current categorization of tests within the MSST. They will then be asked to rank-order tests within the categories by which tests they feel are the best tests of that construct. Experts will also be asked to comment on the proposed scoring mechanism. In round 3, members of the panel will be given the results from the previous round of questions as well as the validity and inter-rater reliability results from items within the MSST. Experts will be asked to rank-order the tests within the MSST for each construct based on these results. Based on the validity and reliability, they will be asked to suggest which tests should remain in the screen and why. The panels' comments will be used to aid in the determination of the items that remain within the comprehensive screen and how the items are characterized and scored. The expected outcome is to create a modified comprehensive performance-based movement system-screening tool (version 2) with acceptable face validity for the next development steps.

Specific Aim 2: Determine the psychometric properties of the comprehensive performance-based movement system screen.

2A) Determine criterion validity of the clinical core stability tests by validating the clinical core screening items within the comprehensive performance based movement system screen against lab-based measures of core stability.

Research Design

This will be a methodological study of the psychometric properties of the tests designed to assess core stability within the comprehensive performance-based screen.

The purpose of this study will be to determine criterion validity by examining the relationship between the clinical tests of core stability and the lab-based measures of core stability. This may result in further modification of the item characterization schematic of screen properties as clinical assessments of core stability may demonstrate different degrees of association to the lab measure.

Methods

Subjects: The population will be athletes (see operational definitions) between the ages of 18-35 in the Philadelphia area. Inclusion criteria will be any athlete currently competing in any sport at a professional, semi-professional, varsity, junior varsity, or club level, with a minimum participation of 10 hours per week in practice and/or strength and conditioning workouts. Exclusion criteria include any of the following: current cervical spine, or lumbar spine injury; any previous injury which still affects his or her ability to play their respective sport (i.e., not cleared for unrestricted participation in their usual sport by the team physician), a diagnosed balance or vestibular disorder, and a current head cold or sinus infection that may affect an individual's balance. Recruitment will occur through the athletic trainers, coaches, and/or team physicians from the University of Pennsylvania (NCAA Division I, 27 varsity teams); Drexel University (NCAA Division I (16 varsity teams); and local CrossFit affiliates in the Philadelphia and South New Jersey area. A priori power analysis using G*Power 3 (Faul et al., 2009) suggests a sample size of 84 to determine the correlation between clinical tests of core stability and lab-based measures with power = 0.80, alpha = 0.05, correlation ρ H1 = 0.3, two-tailed.

Instruments and Measures

Chair and Force Plate for Lab Based Measures of Seated Neuromuscular Control

A seated balance platform will be used to collect static and dynamic lab-based measures of isolated core neuromuscular control. The seat will be placed on top of a multicomponent portable force plate (Kistler Inc) that is connected to a computer and video monitor that allows center of pressure data to be tracked and projected for real-time feedback. A dedicated data collection computer with custom LabView programs is used for data collection through a 32-channel A/D board. All force data will be collected at 2400 Hz. Details and specifications of the chair can be found in Appendix 5.

Procedures: Subjects will be asked to attend one testing session lasting approximately 2.0 hours. Subjects will be asked to refrain from strenuous exercise 24 hours prior to testing session to avoid potential effects of fatigue. The informed consent form will be reviewed with the subject, questions answered (according to HRP 90, 91) and a copy of the consent will be given to the subject, after all signatures are obtained. Demographic and morphological data will be collected as follows: age, sex, height in centimeters, weight in kilograms, leg length in centimeters, tibial length in centimeters, trunk length in centimeters and hand dominance/leg dominance. Subjects will complete Sports Activity Questionnaire (Appendix 9).

After the subject has completed all necessary demographic information, they will perform the lab-based tests of isolated core neuromuscular control. These tests consist of static trunk postural control (eyes open and eyes closed) and dynamic trunk control (limits of stability and target test). The same procedures used in preliminary study 2 will be used (see Appendix 5).

Once subjects have completed the above tests, the subject will perform the MSST. The screen begins with clinical measures of core stability (both neuromuscular control and muscle capacity). Starting with the Core Control Clinical Test (CCCT), subjects will be given detailed instructions followed by a 30-second practice trial and two recorded trials. Subjects will be given a 5-minute rest period before performing the tests of core muscle capacity, which include the trunk extensor endurance (TEE), flexor endurance (FE), and double-leg lowering test (DLLT). One trial of each test will be performed to reduce the effects of fatigue. For each test of core muscle capacity, the subject will be allowed to practice assuming the testing position with feedback from the tester. For each of these tests, the subject is instructed to maintain the test position as long as possible or until the tester stops the test. The core muscle capacity tests are described in detail in the MSST Manual (Appendix 6).

For the remaining sections of the screen, the tests were broken into series based on the progressions of the movement patterns being assessed. The series design allows for the screen to be incorporated into a mass pre-participation evaluation as each series can be set up as a station. The following design was developed for feasibility purposes within our lab; however, variations of the series flow may exist as long as the progression within each series remains as described. Following the core muscle capacity and control tests, the side lying series will be performed on a standard mat table. The series consists of the active hip abduction (AHA) test followed by the active hip abduction resisted (AHAR) test, side bridge (SB), side bridge with hip abduction (SBA), and side bridge with hip abduction resisted (SBAR). Detailed procedures of each test can be found in the MSST Manual (Appendix 6).

The next series performed will be the supine series immediately followed by the bridge series. The supine series starts with the modified Thomas test (MTT) followed by the active straight leg raise (ASLR). The bridge series will be performed next and starts with a bilateral hip bridge (HB) followed by a unilateral hip bridge (UHB), unilateral hip bridge resisted (UHBR), and unilateral hip bridge endurance (UHBE). Detailed procedures are located in the MSST Manual (Appendix 6).

Next, the subject will perform the prone and quadruped series. The series starts with prone hip extension (HE), followed by hip extension with contralateral arm lift (HEUE), flexion clearing test (FLEX), rotary stability (RS), extension clearing test (EXT), and trunk stability push-up (PUSH). The standing series is the next series within the screen. The standing series begins with the squat (SQUAT) followed by the hurdle step (HURDLE), and in-line lunge (LUNGE). Detailed procedures are located in the MSST Manual (Appendix 6).

Next, subjects will perform the upper extremity series followed by the dynamic series. Within the upper extremity series, subjects will be asked to perform a shoulder clearing test (SHO CLR), shoulder mobility (SHO MOB), glenohumeral internal rotation deficit (GIRD), scapular dyskinesis (SCAP DYS) test, and the closed kinetic chain upper extremity test (CKCUEST). The last series performed will be the dynamic series. The series consists of the step down (STEP) test, Y-Balance Test (YBT), and single-leg hop for distance (HOP).

Detailed description of lab procedures, data collection forms and data reduction processes can be found in Appendix 10.

Data Analysis

All statistical analyses will be conducted using Statistical Package for the Social Sciences (version 22.0; SPSS Inc, Chicago, IL). The p-value for statistical significance will be set at < 0.05. Descriptive data including gender, age, height, weight, sport, hours per week activity, and previous injury history will be collected. Pearson correlations will be used to examine the relationship between lab-based measures and clinical tests of core stability. If data are not normally distributed, Spearman's rho will be used to examine the relationship between each of the clinical and lab-based tests. Correlations will be interpreted according to Cohen [0.1-weak, 0.3-moderate, 0.5-strong].[123] A priori, we are considering any correlation greater than or equal to 0.5 as an adequate relationship and thus any clinical test that demonstrates this association will be considered for inclusion in the next draft of the screen. A correlation of 0.5 or greater will represent 25% of the variance in the biomechanical variables of isolated core stability. It is understood that these clinical core stability tests may not be isolating the core region of the body (i.e. there may be some extremity influence) and that some tests may only capture core muscle capacity. Given not all tests for core stability will emphasize neuromuscular control, a battery of tests based on correlations and representing different aspects of core stability may be selected.

The expected outcome is to determine which clinical measures of core stability demonstrate the strongest association with a lab-based measure of isolated core neuromuscular control. The clinical assessment with the strongest association ($r \geq 0.5$) will be included in the next version (version 3) of the MSST to address the neuromuscular control construct of core stability.

2B) Determine screen constructs and inter-rater reliability of tests within the comprehensive performance-based movement system screen.

Research Design

This will be a methodological study aimed at determining the inter-rater reliability of test items within the screen as well test item construct redundancy. This study will allow for further modification of the screen by eliminating items with poor inter-rater reliability as well as items that demonstrate the ability to assess the same constructs.

Methods

Subjects: The subject population from Specific Aim 2a will be used to accomplish Aim 2b. Inclusion and exclusion criteria remain the same.

Instruments and Measures

The modified MSST (version 2) will be used to accomplish Aim 2b.

Procedures

See MSST Manual for detailed procedures of the MSST.

Data Analysis

All statistical analyses will be conducted using Statistical Package for the Social Sciences (version 22.0; SPSS Inc, Chicago, IL). The p-value for statistical significance will be set at ≤ 0.05. Exploratory factor analysis will be used to determine which elements of the comprehensive screen are evaluating the same construct. KMO (>0.5) and Bartlett's test of sphericity ($p<0.05$) will be used to determine if there are an adequate number of items for each factor and to check that the original variables are sufficiently correlated, respectively. If Bartlett's test is not significant ($p < 0.05$), then factor analysis will not be used and Pearson's correlations will determine the relationships between variables.[126] Cohen's kappa will be used to determine the measure of agreement between raters of tests within the comprehensive screen. Inter-rater agreement will be interpreted according to Landis and Koch [<0: no agreement, 0.1-0.20: slight agreement, 0.21-0.40: fair agreement, 0.41-0.60: moderate agreement, 0.61-0.80: substantial agreement, 0.81-0.99: almost perfect agreement].[125] A priori, we are considering any tests with inter-rater agreement of 0.61 or higher (substantial) and eigenvalues greater than 1.0 for the factor analysis as adequate for inclusion in the next version of the screen. At this level of analysis, agreement on whether both raters did or did not observe a fault and the degree of the fault will be assessed. Items with poor inter-rater reliability ($r < 0.6$) and items that are highly correlated or are found to be measuring the same factor will be removed from the MSST to create (version 3) of the assessment. This will increase overall rater reliability, increase efficiency of the overall assessment, and enhance the usability of the MSST.

2C) Determine inter-rater reliability of the composite score on a modified version of the comprehensive performance-based movement system screen in a cohort of athletes.

Research Design

This will be a methodological study aimed at determining the inter-rater reliability of the modified MSST (version 3) composite (total) score.

Methods

Subjects: The subject population from Specific Aim 2a will be used to accomplish Aim 2c. Inclusion and exclusion criteria remain the same.

Instruments and Measures

The modified MSST (version 3) will be used to accomplish Aim 2c.

Procedures

See MSST Manaul for detailed procedures of the MSST.

Data Analysis

All statistical analyses will be conducted using Statistical Package for the Social Sciences (version 22.0; SPSS Inc, Chicago, IL). The p-value for statistical significance will be set at ≤ 0.05. ICC (3,1) will be used to determine the measure of agreement between raters on the comprehensive screen (draft 3) composite score. ICC will be interpreted according to Portney and Watkins.[127] We expect that the MSST (version 3) will demonstrate good to excellent reliability between raters when using the composite score.

Specific Aim 3: Determine the ability of the modified comprehensive performance-based screen to discriminate performance in athletes with and without non-traumatic shoulder pain.

3A) Determine the difference in composite scores on the modified comprehensive screen in athletes with and without non-traumatic shoulder pain.

Research Design

This will be a known groups analysis to test the ability of the MSST (version 3) and determine if the current version of the MSST can discriminate between the performance of athletes who are known to have non-traumatic shoulder pain and those who do not. Using a known groups method allows for us to choose a criterion (i.e. composite score on the comprehensive screen) that can theoretically identify the presence or absence of a certain characteristic (i.e. shoulder pain) [128]. Athletes with shoulder pain may score lower on upper extremity movement pattern tests within the screen due to current shoulder pain and/or dysfunction. Based on the kinetic chain theory, athletes with non-traumatic shoulder pain may exhibit poor movement pattern efficiency in either the upper or lower extremity, and/or the core, and as a result will demonstrate a noted performance difference on these tests within the screen.

Methods

Subjects: Purposive sampling will be used to recruit the same subjects as Specific Aim 2. Subjects with shoulder pain have the following additional criteria: shoulder pain that is non-traumatic in nature, and onset of the injury or pain within the last 6 months. Healthy controls will be matched by age within 5 years, gender, sport group [a) overhead athletes; b) athletes who use their upper extremities in their sports but are not overhead, e.g., lacrosse; and c) athletes who do not use their upper extremities in their sport, e.g., track] and body mass index (BMI) within 5 kg/m^2. A priori power analysis determined a sample size of 68 is needed (34 per group) to achieve significance at $p<0.05$ and power of 0.80 for a two-tailed independent t-test with an effect size of 0.7. The effect size was chosen because it is considered to be a large effect [123].

Instruments and Measures

The modified MSST (version 3) will be used to accomplish Aim 3a.

Procedures

See MSST Manual for detailed procedures of the MSST.

Data Analysis

All statistical analyses will be conducted using Statistical Package for the Social Sciences (version 22.0; SPSS Inc, Chicago, IL). The p-value for statistical significance will be set at ≤ 0.05. An independent t-test will be used to determine the relationship between the modified comprehensive screen composite score in athletes with and without non-traumatic shoulder pain. We expect that MSST will be able to discriminate performance differences between athletes with and without pain.

3B) Identify items in the modified comprehensive performance-based movement system screen that optimally classify athletes with and without non-traumatic shoulder pain.

Research Design

This will be a cross-sectional design to determine the ability of items in the comprehensive performance-based movement system-screening tool to identify the prevalence of non-traumatic shoulder pain in athletes.

Methods

Subjects: The subject population from Aim 3a will be used for this aim.

Instruments and Measures

The modified MSST (version 3) will be used to accomplish Aim 3b.

Procedures

See MSST Manual for detailed procedures of the MSST.

Data Analysis

All statistical analyses will be conducted using Statistical Package for the Social Sciences (version 22.0; SPSS Inc, Chicago, IL). The p-value for statistical significance will be set at ≤ 0.05. Logistic regression will be used to identify which clinical tests within the MSST (version 3) classify athletes with and without shoulder pain. Variables selected for input into the logistic regressions will be determined by use of independent T-tests. If data are not normally distributed, a Mann-Whitney U will be used. From these tests, the variables that are found to differ between groups ($p \leq 0.1$) will be checked for multicollinearity. Those variables that meet the assumptions will be entered into the regression model. Odds ratios and 95% confidence intervals for the odds ratios will be calculated.

We expect that the items that test upper extremity movement patterns and core stability will be the best predictors of non-traumatic shoulder pain. Determining these predictors may allow for creation of a subset of tests that could be used as a first level screen for upper extremity athletes. As the MSST is attempting to assess major deviations from expected performance of movement patterns and core stability, any tests found to be significant predictors of shoulder pain may be considered as part of an initial movement screen. Degraded performance on these measures should lead to further movement analysis using additional tests item or from the athlete's assigned clinician (Athletic Trainer or Physical Therapist) in an effort to confirm or identify specific impairments and develop an appropriate intervention.

LIMITATIONS

The current screen (version 3) has not been assessed for test-retest reliability, to date. This could potentially limit our ability to interpret whether performance differences between groups falls within the screen's standard measurement error. Future work will need to address this as the next step in the development of a reliable clinical assessment. The proposed project does not include examination of movement pattern efficiency from a biomechanical perspective with respect to muscle activation, timing patterns, or kinematics. Future research should examine these variables to better interpret the potential meaning of poor movement efficiency and to potentially direct intervention to resolve movement impairment. The study design does not allow us to determine if degraded performance within core stability tests, or movement pattern efficiency were present prior to the shoulder injury or if the performance on these tests are a result of non-traumatic shoulder pain. The findings are not be generalizable to individuals who exercise/train less than 10 hours per week, who are under the age of 18, or older than 35. Future work should prospectively assess the ability of the MSST to predict upper and lower extremity injury in athletes. The outcomes of this study will however provide preliminary data for a larger, more costly prospective longitudinal studies designed to answer these important questions.

POTENTIAL PROBLEMS AND ALTERNATIVE STRATEGIES

We do not expect to have problems with recruitment of athletes for our study given our personal relationship with the medical staff and coaches of the local athletic departments and CrossFit affiliates. If needed, other schools in the greater Philadelphia area will be contacted (Temple University, Ursinus College, Villanova, LaSalle, St. Joseph's, Rowan, and Rutgers).

Equipment problems could occur during biomechanical testing, which we will minimize with regular calibration and monitoring of the equipment. Any resultant loss of data will be dealt with statistically.

Fatigue with any element of testing is a concern as it has the potential to introduce an uncontrolled modifying effect on test performance. However, our pilot work indicated that no portion of the test fatigued the pilot subjects enough to effect subsequent portions of the test, and rest breaks have been built into the procedure. Rating of perceived exertion (RPE) data using the Borg Scale (6-20, with 6 being no exertion at all and 20 being maximal exertion) was collected on all subjects (N=65) after the lab-based measure of core stability and the clinical core stability tests. No subjects reported a score higher than a 17 (very hard) and every subject reported a score of 6 or 7 (no exertion at all to extremely light) prior to moving to the next series of tests.

To date, test-retest reliability of the MSST has not been established. Obtaining subjects who are willing to return for a 2-hour session without compensation is not part of the current planned psychometric assessment, but will need to be completed in the future.

Some data may be inaccurate or biased as the injury history information is self-reported and there may be a lack of motivation or attention during the testing protocol. This issue will be mitigated by follow-up questions to the subjects regarding injury history and tester encouragement throughout the protocol.

Statistically, there are other options for analysis that may assist in data interpretation of the utility of the screen for determine of performance degradation or injury risk. ROC curves, diagnostic accuracy assessment, and discriminant analysis are other statistical approaches that could also be used, and have been considered, to assess and interpret the validity of the MSST.

During modifications of the screen, some tests may be removed and it is important to note that the removal of these tests may affect screen performance. Performance on the removed test may have affected performance on another test, however, we do not know to what extent.

It should be noted that the current screen is in the early stages of development, with a focus on the preliminary testing of the psychometric properties and utility of the screen in an athletic population. Realistically, a comprehensive screen that addresses all possible movement pattern impairments may be too time consuming to apply in a mass-screening scenario. I am considering another possible approach that includes only one to two tests to assess upper or lower extremity movement pattern efficiency and one test to assess core stability. The tests used would be based on sport classification. For example, overhead athletes would utilize upper extremity movement pattern and core tests, while soccer players would utilize the lower extremity movement pattern and core tests. From here, the next step would be to create stages of testing, which include the initial screen and a follow-up or confirmatory screen to be done by the team's athletic trainer/clinician if any potential obvious performance deviations are observed in the initial screen.

REFERENCES

1. Dick R, Agel J, Marshall SW. National Collegiate Athletic Association Injury Surveillance System commentaries: introduction and methods. *J Athl Train.* Apr-Jun 2007;42(2):173-182.

2. Hootman JM, Dick R, Agel J. Epidemiology of collegiate injuries for 15 sports: summary and recommendations for injury prevention initiatives. *J Athl Train.* Apr-Jun 2007;42(2):311-319.

3. Hewett TE, Myer GD, Ford KR. Reducing knee and anterior cruciate ligament injuries among female athletes: a systematic review of neuromuscular training interventions. *J Knee Surg.* Jan 2005;18(1):82-88.

4. Leetun DT, Ireland ML, Willson JD, et al. Core stability measures as risk factors for lower extremity injury in athletes. *Med Sci Sports Exerc.* Jun 2004;36(6):926-934.

5. Liemohn WP, Baumgartner TA, Fordham SR, et al. Quantifying core stability: a technical report. *J Strength Cond Res.* 2010;24(2):575-579.

6. Kibler WB, Press J, Sciascia A. The role of core stability in athletic function. *Sports Med.* 2006;36(3):189-198.

7. Hewett TE, Myer GD, Ford KR, et al. Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: a prospective study. *Am J Sports Med.* Apr 2005;33(4):492-501.

8. Aguinaldo AL, Buttermore J, Chambers H. Effects of upper trunk rotation on shoulder joint torque among baseball pitchers of various levels. *J Appl Biomech.* Feb 2007;23(1):42-51.

9. Zazulak BT, Hewett TE, Reeves NP, et al. Deficits in neuromuscular control of the trunk predict knee injury risk: a prospective biomechanical-epidemiologic study. *Am J Sports Med.* Jul 2007;35(7):1123-1130.

10. Onate JA, Dewey T, Kollock RO, et al. Real-time intersession and interrater reliability of the functional movement screen. *J Strength Cond Res.* Feb 2012;26(2):408-415.

11. Cholewicki J, Silfies SP, Shah RA, et al. Delayed trunk muscle reflex responses increase the risk of low back injuries. *Spine (Phila Pa 1976).* Dec 1 2005;30(23):2614-2620.

12. Ireland ML, Willson JD, Ballantyne BT, et al. Hip strength in females with and without patellofemoral pain. *J Orthop Sports Phys Ther.* Nov 2003;33(11):671-676.

13. Tate A, Turner GN, Knab SE, et al. Risk factors associated with shoulder pain and disability across the lifespan of competitive swimmers. *J Athl Train.* Mar-Apr 2012;47(2):149-158.

14. Garrison JC, Arnold A, Macko MJ, et al. Baseball players diagnosed with ulnar collateral ligament tears demonstrate decreased balance compared to healthy controls. *J Orthop Sports Phys Ther.* Oct 2013;43(10):752-758.

15. Zazulak BT, Hewett TE, Reeves NP, et al. The effects of core proprioception on knee injury: a prospective biomechanical-epidemiological study. *Am J Sports Med.* Mar 2007;35(3):368-373.

16. Silfies SP, Ebaugh D, Pontillo M, et al. Critical Review of the Impact of "Core Stability" on Upper Extremity Athletic Injury and Performance. *Braz J Phys Ther.* 2015;In Press.

17. Kibler WB, McMullen J. Scapular dyskinesis and its relation to shoulder pain. *J Am Acad Orthop Surg.* Mar-Apr 2003;11(2):142-151.

18. Sciascia A, Thigpen C, Namdari S, et al. Kinetic chain abnormalities in the athletic shoulder. *Sports Med Arthrosc.* Mar 2012;20(1):16-21.

19. Kibler WB, Thomas SJ. Pathomechanics of the throwing shoulder. *Sports Med Arthrosc.* Mar 2012;20(1):22-29.

20. Cook G, Burton L, Hoogenboom B. Pre-participation screening: the use of fundamental movements as an assessment of function - part 2. *N Am J Sports Phys Ther.* Aug 2006;1(3):132-139.

21. Cook G, Burton L, Hoogenboom B. Pre-participation screening: the use of fundamental movements as an assessment of function - part 1. *N Am J Sports Phys Ther.* May 2006;1(2):62-72.

22. Tarara DT, Hegedus EJ, Taylor JB. Real-time test-retest and interrater reliability of select physical performance measures in physically active college-aged students. *Int J Sports Phys Ther.* Dec 2014;9(7):874-887.

23. McKeown I, Taylor-McKeown K, Woods C, et al. Athletic ability assessment: a movement assessment protocol for athletes. *Int J Sports Phys Ther.* Dec 2014;9(7):862-873.

24. McGill SM, Childs A, Liebenson C. Endurance times for low back stabilization exercises: clinical targets for testing and training from a normal database. *Arch Phys Med Rehabil.* Aug 1999;80(8):941-944.

25. Okada T, Huxel KC, Nesser TW. Relationship between core stability, functional movement, and performance. *J Strength Cond Res.* Jan 2011;25(1):252-261.

26. Harrington S, Meisel C, Tate A. A cross-sectional study examining shoulder pain and disability in Division I female swimmers. *J Sport Rehabil.* Feb 2014;23(1):65-75.

27. Cholewicki J, Polzhofer GK, Radebold A. Postural control of trunk during unstable sitting. *J Biomech.* Dec 2000;33(12):1733-1737.

28. National Center for Injury Prevention and Control. CDC Injury Research Agenda. US Department of Health and Human Services; 2002.

29. Powell JW, Barber-Foss KD. Injury patterns in selected high school sports: a review of the 1995-1997 seasons. *J Athl Train.* Jul 1999;34(3):277-284.

30. Brown G. College sports participation rates continue upward trend. 2011; http://www.ncaa.org/wps/wcm/connect/public/NCAA/Resources/Latest+News/2011/November/College+sports+participation+rates+continue+upward+trend.

31. NCAA. *NCAA Sports Sponsorship and Participation Rates Report.* 2013.

32. Griffin LY, Albohm MJ, Arendt EA, et al. Understanding and preventing noncontact anterior cruciate ligament injuries: a review of the Hunt Valley II meeting, January 2005. *Am J Sports Med.* Sep 2006;34(9):1512-1532.

33. Laudner K, Sipes, R. The Incidence of Shoulder Injury among Collegiate Overhead Athletes. *J Intercollegiate Sport.* 2009;2:260-268.

34. McFarland EG, Wasik M. Epidemiology of collegiate baseball injuries. *Clin J Sport Med.* Jan 1998;8(1):10-13.

35. Songer TJ, LaPorte RE. Disabilities due to injury in the military. *Am J Prev Med.* Apr 2000;18(3 Suppl):33-40.

36. Lincoln AE, Smith GS, Amoroso PJ, et al. The natural history and risk factors of musculoskeletal conditions resulting in disability among US Army personnel. *Work.* 2002;18(2):99-113.

37. Jones BH, Knapik JJ. Physical training and exercise-related injuries. Surveillance, research and injury prevention in military populations. *Sports Med.* Feb 1999;27(2):111-125.

38. Knapik JJ, Bullock SH, Canada S, et al. Influence of an injury reduction program on injury and fitness outcomes among soldiers. *Inj Prev.* Feb 2004;10(1):37-42.

39. Knapik JJ, Canham-Chervak M, Hauret K, et al. Discharges during U.S. Army basic training: injury rates and risk factors. *Mil Med.* Jul 2001;166(7):641-647.

40. Knapik JJ, Jones SB, Darakjy S, et al. Injury rates and injury risk factors among U.S. Army wheel vehicle mechanics. *Mil Med.* Sep 2007;172(9):988-996.

41. Gregg S. Musculoskeletal Conditions per M2 Database Analysis for FY 2007. Ft. Sam Houston2008.

42. Activity AMS. U. S. Army for Health Promotion and Preventative Medicine. 2005; http://afhsc.army.mil/home.

43. Mandelbaum BR, Silvers HJ, Watanabe DS, et al. Effectiveness of a neuromuscular and proprioceptive training program in preventing anterior cruciate ligament injuries in female athletes: 2-year follow-up. *Am J Sports Med.* Jul 2005;33(7):1003-1010.

44. Hewett TE, Torg JS, Boden BP. Video analysis of trunk and knee motion during non-contact anterior cruciate ligament injury in female athletes: lateral trunk and knee abduction motion are combined components of the injury mechanism. *Br J Sports Med.* Jun 2009;43(6):417-422.

45. Hagglund M, Walden M, Ekstrand J. Previous injury as a risk factor for injury in elite football: a prospective study over two consecutive seasons. *Br J Sports Med.* Sep 2006;40(9):767-772.

46. Messina DF, Farney WC, DeLee JC. The incidence of injury in Texas high school basketball. A prospective study among male and female athletes. *Am J Sports Med.* May-Jun 1999;27(3):294-299.

47. Boden BP, Griffin LY, Garrett WE, Jr. Etiology and Prevention of Noncontact ACL Injury. *Phys Sportsmed.* Apr 2000;28(4):53-60.

48. Griffin LY, Agel J, Albohm MJ, et al. Noncontact anterior cruciate ligament injuries: risk factors and prevention strategies. *J Am Acad Orthop Surg.* May-Jun 2000;8(3):141-150.

49. Croisier JL, Ganteaume S, Binet J, et al. Strength imbalances and prevention of hamstring injury in professional soccer players: a prospective study. *Am J Sports Med.* Aug 2008;36(8):1469-1475.

50. Chorba RS, Chorba DJ, Bouillon LE, et al. Use of a functional movement screening tool to determine injury risk in female collegiate athletes. *N Am J Sports Phys Ther.* Jun 2010;5(2):47-54.

51. Teyhen D, Bergeron MF, Deuster P, et al. Consortium for health and military performance and American College of Sports Medicine Summit: utility of functional movement assessment in identifying musculoskeletal injury risk. *Curr Sports Med Rep.* Jan-Feb 2014;13(1):52-63.

52. Sahrmann SA. The human movement system: our professional identity. *Phys Ther.* Jul 2014;94(7):1034-1042.

53. Zazulak B, Cholewicki J, Reeves NP. Neuromuscular control of trunk stability: clinical implications for sports injury prevention. *J Am Acad Orthop Surg.* Sep 2008;16(9):497-505.

54. Fleisig GS, Barrentine SW, Escamilla RF, et al. Biomechanics of overhand throwing with implications for injuries. *Sports Med.* Jun 1996;21(6):421-437.

55. Elliot BC MR, Noffal GJ. Contributions of the upper limb segment rotations during the power serve in tennis. *Journal of Applied Biomechanics.* 1995;11(4):433-442.

56. Panjabi MM. The stabilizing system of the spine. Part I. Function, dysfunction, adaptation, and enhancement. *J Spinal Disord.* Dec 1992;5(4):383-389; discussion 397.

57. Liemohn WP, Baumgartner TA, Gagnon LH. Measuring core stability. *J Strength Cond Res.* Aug 2005;19(3):583-586.

58. Reeves NP, Everding VQ, Cholewicki J, et al. The effects of trunk stiffness on postural control during unstable seated balance. *Exp Brain Res.* Oct 2006;174(4):694-700.

59. Baumhauer JF, Alosa DM, Renstrom AF, et al. A prospective study of ankle injury risk factors. *Am J Sports Med.* Sep-Oct 1995;23(5):564-570.

60. Fredericson M, Cookingham CL, Chaudhari AM, et al. Hip abductor weakness in distance runners with iliotibial band syndrome. *Clin J Sport Med.* Jul 2000;10(3):169-175.

61. Knapik JJ, Bauman CL, Jones BH, et al. Preseason strength and flexibility imbalances associated with athletic injuries in female collegiate athletes. *Am J Sports Med.* Jan-Feb 1991;19(1):76-81.

62. Nadler SF, Malanga GA, DePrince M, et al. The relationship between lower extremity injury, low back pain, and hip muscle strength in male and female collegiate athletes. *Clin J Sport Med.* Apr 2000;10(2):89-97.

63. Orchard J, Marsden J, Lord S, et al. Preseason hamstring muscle weakness associated with hamstring muscle injury in Australian footballers. *Am J Sports Med.* Jan-Feb 1997;25(1):81-85.

64. Soderman K, Alfredson H, Pietila T, et al. Risk factors for leg injuries in female soccer players: a prospective investigation during one out-door season. *Knee Surg Sports Traumatol Arthrosc.* Sep 2001;9(5):313-321.

65. Devan MR, Pescatello LS, Faghri P, et al. A Prospective Study of Overuse Knee Injuries Among Female Athletes With Muscle Imbalances and Structural Abnormalities. *J Athl Train.* Sep 2004;39(3):263-267.

66. Chaudhari AM, McKenzie CS, Pan X, et al. Lumbopelvic control and days missed because of injury in professional baseball pitchers. *Am J Sports Med.* Nov 2014;42(11):2734-2740.

67. Hodges PW, Richardson CA. Contraction of the abdominal muscles associated with movement of the lower limb. *Phys Ther.* Feb 1997;77(2):132-144.

68. Bergmark A. Stability of the lumbar spine. A study in mechanical engineering. *Acta Orthop Scand Suppl.* 1989;230:1-54.

69. Hirashima M, Kadota H, Sakurai S, et al. Sequential muscle activity and its functional role in the upper extremity and trunk during overarm throwing. *J Sports Sci.* Apr 2002;20(4):301-310.

70. Ireland ML. The female ACL: why is it more prone to injury? *Orthop Clin North Am.* Oct 2002;33(4):637-651.

71. Myer GD, Ford KR, Khoury J, et al. Biomechanics laboratory-based prediction algorithm to identify female athletes with high knee loads that increase risk of ACL injury. *Br J Sports Med.* Apr 2011;45(4):245-252.

72. Burkhart SS, Morgan CD, Kibler WB. The disabled throwing shoulder: spectrum of pathology. Part II: evaluation and treatment of SLAP lesions in throwers. *Arthroscopy.* May-Jun 2003;19(5):531-539.

73. Hong DA, Cheung TK, Roberts EM. A three-dimensional, six-segment chain analysis of forceful overarm throwing. *J Electromyogr Kinesiol.* Apr 2001;11(2):95-112.

74. Sciascia A, Cromwell R. Kinetic chain rehabilitation: a theoretical framework. *Rehabil Res Pract.* 2012;2012:853037.

75. Wadsworth CT, Krishnan R, Sear M, et al. Intrarater reliability of manual muscle testing and hand-held dynametric muscle testing. *Phys Ther.* Sep 1987;67(9):1342-1347.

76. Gribble PA, Hertel J, Plisky P. Using the Star Excursion Balance Test to assess dynamic postural-control deficits and outcomes in lower extremity injury: a literature and systematic review. *J Athl Train.* May-Jun 2012;47(3):339-357.

77. Brumitt J, Heiderscheit BC, Manske RC, et al. Lower extremity functional tests and risk of injury in division iii collegiate athletes. *Int J Sports Phys Ther.* Jun 2013;8(3):216-227.

78. Crossley KM, Zhang WJ, Schache AG, et al. Performance on the single-leg squat task indicates hip abductor muscle function. *Am J Sports Med.* Apr 2011;39(4):866-873.

79. Cook G, Burton L, Hoogenboom BJ, et al. Functional movement screening: the use of fundamental movements as an assessment of function - part 1. *Int J Sports Phys Ther.* May 2014;9(3):396-409.

80. Moreau CE, Green BN, Johnson CD, et al. Isometric back extension endurance tests: a review of the literature. *J Manipulative Physiol Ther.* Feb 2001;24(2):110-122.

81. Lanning CL, Uhl TL, Ingram CL, et al. Baseline values of trunk endurance and hip strength in collegiate athletes. *J Athl Train.* Oct-Dec 2006;41(4):427-434.

82. Krause DA, Youdas JW, Hollman JH, et al. Abdominal muscle performance as measured by the double leg-lowering test. *Arch Phys Med Rehabil.* Jul 2005;86(7):1345-1348.

83. Radebold A, Cholewicki J, Panjabi MM, et al. Muscle response pattern to sudden trunk loading in healthy individuals and in patients with chronic low back pain. *Spine (Phila Pa 1976).* Apr 15 2000;25(8):947-954.

84. Shultz R, Anderson SC, Matheson GO, et al. Test-retest and interrater reliability of the functional movement screen. *J Athl Train.* May-Jun 2013;48(3):331-336.

85. Minick KI, Kiesel KB, Burton L, et al. Interrater reliability of the functional movement screen. *J Strength Cond Res.* Feb 2010;24(2):479-486.

86. Whiteside D, Deneweth JM, Pohorence MA, et al. Grading the Functional Movement Screen: A Comparison of Manual (Real-Time) and Objective Methods. *J Strength Cond Res.* Aug 26 2014.

87. Kiesel K, Plisky PJ, Voight ML. Can Serious Injury in Professional Football be Predicted by a Preseason Functional Movement Screen? *N Am J Sports Phys Ther.* Aug 2007;2(3):147-158.

88. Knapik JJ, Cosio-Lima LM, Reynolds KL, et al. Efficacy of functional movement screening for predicting injuries in coast guard cadets. *J Strength Cond Res.* May 2015;29(5):1157-1162.

89. Butler RJ, Contreras M, Burton LC, et al. Modifiable risk factors predict injuries in firefighters during training academies. *Work.* Jan 1 2013;46(1):11-17.

90. Lisman P, O'Connor FG, Deuster PA, et al. Functional movement screen and aerobic fitness predict injuries in military training. *Med Sci Sports Exerc.* Apr 2013;45(4):636-643.

91. Garrison M, Westrick R, Johnson MR, et al. Association between the functional movement screen and injury development in college athletes. *Int J Sports Phys Ther.* Feb 2015;10(1):21-28.

92. Burton SL. *Performance and injury predictability during firefighter candidate training (PhD Dissertation)*. Blacksburg, VA, Virginia Tech; 2006.

93. Hoover D, Killian CB, Bourcier B, et al. Predictive validity of the Functional Movement Screen in a population of recreational runners training for a half marathon. 55th Annual Meeting of the American College of Sports Medicine; 2008; Indianapolis, Indiana.

94. Morrell MD. *Lower extremity injury predictability of the Functional Movement Screen and the Star Excursion Balance Test (Master of Science Dissertation).* Toledo, OH, University of Toledo; 2012.

95. Munce TA, Dorman JC, Odney TO, et al. Using functional movement tests to assess injury risk and predict performance in Collegiate basketball players. American College of Sports Medicine Annual Meeting; 2012; San Francisco, CA.

96. Sorenson EA. *Functional movement screen as a predictor of injury in high school basketball athletes (Doctor of Philosophy Dissertation).* . Eugene, OR, University of Oregon; 2009.

97. Winke MR, Dalton K, Mendell J, et al. Prediction of in-season injuries using a preseason Functional Movement Screen in Collegiate athletes. American College of Sports Medicine Annual Meeting; 2012; San Francisco, CA.

98. Perry FT, Koehle MS. Normative data for the functional movement screen in middle-aged adults. *J Strength Cond Res.* Feb 2013;27(2):458-462.

99. Schneiders AG, Davidsson A, Horman E, et al. Functional movement screen normative values in a young, active population. *Int J Sports Phys Ther.* Jun 2011;6(2):75-82.

100. Mckeown I, Ball N. Current practices of long term athlete development of junior athletes in high performance sport environments. *Journal of Australian Strength and Conditioning.* 2013;21(1):16-25.

101. Shanley E, Thigpen CA, Clark JC, et al. Changes in passive range of motion and development of glenohumeral internal rotation deficit (GIRD) in the professional pitching shoulder between spring training in two consecutive years. *J Shoulder Elbow Surg.* Nov 2012;21(11):1605-1612.

102. Wilk KE, Macrina LC, Fleisig GS, et al. Correlation of glenohumeral internal rotation deficit and total rotational motion to shoulder injuries in professional baseball pitchers. *Am J Sports Med.* Feb 2011;39(2):329-335.

103. Dines JS, Frank JB, Akerman M, et al. Glenohumeral internal rotation deficits in baseball players with ulnar collateral ligament insufficiency. *Am J Sports Med.* Mar 2009;37(3):566-570.

104. Smith CA, Chimera NJ, Warren M. Association of y balance test reach asymmetry and injury in division I athletes. *Med Sci Sports Exerc.* Jan 2015;47(1):136-141.

105. Plisky PJ, Rauh MJ, Kaminski TW, et al. Star Excursion Balance Test as a predictor of lower extremity injury in high school basketball players. *J Orthop Sports Phys Ther.* Dec 2006;36(12):911-919.

106. Miller SJ, Denegar CR. Original research reports – intratester and intertester reliability during the star excursion balance tests. *J Sport Rehabil.* 2010;9(2):104-116.

107. Tucci HT, Martins J, Sposito Gde C, et al. Closed Kinetic Chain Upper Extremity Stability test (CKCUES test): a reliability study in persons with and without shoulder impingement syndrome. *BMC Musculoskelet Disord.* 2014;15:1.

108. Pontillo M, Spinelli B, Sennett B. Prediction of in-season shoulder injury from preseason testing in Division I collegiate football players. *Sports Health.* 2015;6(6):497-503.

109. Goldbeck T, Davies G. Test-retest reliability of the closed kinetic chain upper extremity stability test: a clinical field test. *Journal of Sports Rehabilitation.* 2000;9:35-45.

110. Pontillo M, Huffman G, Sennett B. Profile of upper extremity rotator cuff strength and function in division I collegiate athletes. *J Orthop Sports Phys Ther.* 2011;41(1):A39-A51.

111. Nelson-Wong E, Flynn T, Callaghan JP. Development of active hip abduction as a screening test for identifying occupational low back pain. *J Orthop Sports Phys Ther.* Sep 2009;39(9):649-657.

112. Ardern CL, Webster KE, Taylor NF, et al. Return to the preinjury level of competitive sport after anterior cruciate ligament reconstruction surgery: two-thirds of patients have not returned by 12 months after surgery. *Am J Sports Med.* Mar 2011;39(3):538-543.

113. Logerstedt D, Grindem H, Lynch A, et al. Single-legged hop tests as predictors of self-reported knee function after anterior cruciate ligament reconstruction: the Delaware-Oslo ACL cohort study. *Am J Sports Med.* Oct 2012;40(10):2348-2356.

114. Butowicz CM, Pontillo M, Milner CE, et al. Relationships between Functional Movement Screen, Y-Balance Test and Biomechanical Measures of Core Stability. . *Med Sci Sports Exerc.* 2014;46(5):696.

115. Munro AG, Herrington LC. Between-session reliability of four hop tests and the agility T-test. *J Strength Cond Res.* May 2011;25(5):1470-1477.

116. Kibler WB, Sciascia A. Current concepts: scapular dyskinesis. *Br J Sports Med.* Apr 2010;44(5):300-305.

117. Ferreira PH, Ferreira ML, Maher CG, et al. Specific stabilisation exercise for spinal and pelvic pain: a systematic review. *Aust J Physiother.* 2006;52(2):79-88.

118. Lee D. *The Pelvic Girdle: An Approach to the Examination and Treatment of the Lumbo-Pelvic-Hip Complex.* 3rd ed. London, England: Churchill Livingstone; 2007.

119. Noehren B, Abraham A, Curry M, et al. Evaluation of proximal joint kinematics and muscle strength following ACL reconstruction surgery in female athletes. *J Orthop Res.* Oct 2014;32(10):1305-1310.

120. Miller MM, Grooms D, Schussler E, et al. Single Leg Glute Bridge: A Clinical Test for Gluteal Muscle Endurance. *Med Sci Sports Exerc.* 2013;45(5):430-430.

121. Okubo Y, Kaneoka K, Imai A, et al. Electromyographic analysis of transversus abdominis and lumbar multifidus using wire electrodes during lumbar stabilization exercises. *J Orthop Sports Phys Ther.* Nov 2010;40(11):743-750.

122. Plisky PJ, Gorman PP, Butler RJ, et al. The reliability of an instrumented device for measuring components of the star excursion balance test. *N Am J Sports Phys Ther.* May 2009;4(2):92-99.

123. Cohen J. *Statistical Power Analysis for the Behavioral Sciences.* New Jersey: Lawrence Erlbaum Associates, Inc.; 1988.

124. Cohen J. A coefficient of agreement for nominal scales. *Educ Psychol Meas.* 1960;20:37-46.

125. Landis JR, Koch GG. The measurement of observer agreement for categorical data. *Biometrics.* Mar 1977;33(1):159-174.

126. Field A. *Discovering Statistics Using SPSS.* Third Edition ed. London: Sage Publications, Ltd; 2009.

127. Portney LG, Watkins MP. *Foundations of Clinical Research: Applications to Research.* Third Edition ed. New Jersey: Pearson Education, Inc.; 2009.

128. Portney L, Watkins M. *Foundations of Clinical Research: Applications to Practice.* 3rd ed ed. Upper Saddle River, NJ: Prentice Hall; 2009.

CHAPTER TWO: VALIDATION OF CLINICAL TESTS OF CORE STABILITY: AN A PRIORI HYPOTHESES CONVERGENT AND DIVERGENT VALIDITY APPROACH

Running Head: Clinical core stability assessment

COURTNEY M. BUTOWICZ, MSEd, CSCS[1]; D. DAVID EBAUGH, PhD, PT[1,2]; CLARE MILNER, PhD, FACSM[1]; MARISSA PONTILLO, PT, DPT, SCS[1,3], SHERI P.SILFIES. PhD, PT[1]

[1] Physical Therapy & Rehabilitation Sciences Department, Drexel University, Philadelphia, PA, USA

[2] Health Sciences Department, Drexel University, Philadelphia, PA, USA

[3] GSPP Penn Therapy and Fitness at Penn Sports Medicine Center, Philadelphia, PA, USA

Correspondence: Address all correspondence to Sheri P. Silfies, PT, PhD, Drexel University, Rehabilitation Sciences Spine Research Laboratory, Three Parkway, Mail Stop 7-502, Philadelphia, PA 19102-1192, USA. Tel: (267) 359-5580; Fax: (267) 359-5576.
Email: silfies@drexel.edu

Statement of Support: This work was supported in part by The American Physical Therapy Association, Sports Section Legacy Fund.

ABSTRACT

Background: Poor core stability is a proposed risk factor for low back and extremity injuries in athletes. Theoretically, optimal core stability requires muscle capacity (strength and endurance), and neuromuscular control. Several clinical tests have been proposed to assess core stability; however, it is unknown how well they assess neuromuscular control when compared to lab-based measures of isolated core neuromuscular control.

Purpose/Hypothesis: The purposes of this study were to determine the construct validity of commonly used and novel clinical tests proposed to assess the neuromuscular aspects of core stability. We hypothesized that clinical tests of neuromuscular control would be moderately correlated to the lab-based measures while clinical tests of muscle capacity would not be moderately correlated.

Study Design: Cross-Sectional design

Methods: Eighty collegiate athletes completed a lab-based test of isolated core neuromuscular control, clinical tests of neuromuscular control [active hip abduction test (AHA), side bridge with active hip abduction test (SBAHA), trunk stability push up (TSPU), rotary stability test (RS), unilateral hip bridge endurance test (UHBE), and clinical core control test (CCCT)] and clinical tests of muscle capacity [the flexor endurance test (FLEX), extensor endurance test (EXT), double-leg lowering test (DLLT)].

Results: None of the clinical tests of core neuromuscular control demonstrated acceptable convergent validity. Correlational analyses revealed little to no relationship between the

UHBE, DLLT, and lab-based variables of neuromuscular control. There were small significant ($p<0.05$) correlations between the CCCT, EXT, TSPU and dynamic directional neuromuscular control (DCMVEL) (r_s = 0.26, 0.22, -0.23, respectively). There were small significant ($p<0.05$) correlations between the FLEX, SBAHA, RS and dynamic precision neuromuscular control (PCCEA) (r_s = -0.21, -0.24, -0.22, respectively).

Conclusions: None of the clinical tests of core stability demonstrated acceptable construct validity for assessing core neuromuscular control in an athletic population. Assessments assumed to assess muscle capacity were not significantly correlated to our lab-based measures of isolated core neuromuscular control, suggesting they are assessing a different construct (muscle capacity).

Levels of Evidence: Level III

Keywords: athletic injuries, neuromuscular control, core stability

INTRODUCTION

Athletes are required to perform complex movements at varying speeds in multiple planes during sports related tasks. These demands and challenges associated with sporting activities come with an inherent risk of injury. There are approximately 7 million people treated for sports-related injuries in the United States each year, equating to over $500 million in emergency room costs.[1,2] In collegiate athletics alone, there are over 12,500 musculoskeletal injuries each year.[3] Non-contact injuries, such as an ACL rupture or non-traumatic shoulder pain, account for nearly 40% of all injuries sustained during practices and 20% of injuries incurred during sanctioned games.[4] Hence, there is a growing demand for a better understanding of the risk factors associated with non-contact musculoskeletal injury in athletes. Impaired core stability is a proposed risk factor of low back and extremity injury in an athletic population.[5-8] As a result, core stability training and assessments have become popular tenants of many training programs and rehabilitation interventions.[9]

Core stability can be defined as the ability to control the motion, position and stiffness of the trunk and pelvis relative to the extremities to allow for optimal generation, transfer, and dissipation of forces between body segments.[10] Theoretically, optimal core stability requires neuromuscular control and muscle capacity of the trunk, pelvis, proximal upper and lower extremity musculature.[11] Neuromuscular control is defined as the ability of an individual to effectively respond to internal and external perturbations via synchronized muscular responses.[12] Muscular capacity refers to the strength and endurance of the musculature. In order to adequately assess core stability in an athlete, clinical tests should assess muscle capacity and neuromuscular control in static and dynamic conditions.

Clinical core stability tests may include both qualitative and quantitative measures of the trunk, pelvis, and proximal extremity neuromuscular control, as well as muscle capacity. Clinical endurance tests are quantified by the amount of time the subject can hold the test position (seconds), while neuromuscular control tests may be quantified using a movement quality ordinal grading scale. Commonly reported muscle capacity tests include the trunk extensor endurance, trunk flexor endurance, and double-leg lowering tests (Figure1). Core muscle endurance impairments have been associated with an increased risk of injury in athletes, while decreased trunk/pelvis/hip extensor muscle endurance is associated with low back pain in non-athletes.[13,14]

Clinical tests of the neuromuscular control aspect of core stability are less prevalent and often do not isolate core musculature (e.g., trunk stability push-up, active hip abduction). The active hip abduction test is a proposed assessment of lumbopelvic control during performance of a low-demand functional lower extremity activity.[15] Poor performance on this test predicted the development of low back pain in previously asymptomatic healthy adults (OR: 3.85, 95% CI: 1.05-19.07).[15] The side bridge with active hip abduction is proposed to assess lateral trunk stability as, theoretically, performance of the test requires core stability to maintain the position of the trunk and pelvis as the leg is abducted.[16] Evidence suggests significant activation of the transverse abdominus and external oblique (on the support side) during the side bridge with active hip abduction test.[17] The unilateral hip bridge endurance test (UHBE) requires significant activation of the lumbar multifidus and erector spinae musculature and was recently validated as a clinical assessment of core stability.[17,18] In a healthy active population, the UHBE demonstrated a moderate significant correlation with a lab-based measure of isolated core neuromuscular control (r_s = -0.49 to -0.56, $p<0.05$).[18] However, the psychometric properties of this test have not been reported, and the utility of this test in an athletic population is unknown.

The trunk stability pushup (PUSH) and rotary stability (RS) tests are components within the Functional Movement Screen that theoretically require core stability for optimal test performance.[19,20] The PUSH reportedly assesses the ability to stabilize the core during a closed chain upper extremity task.[19] The RS reportedly assesses multi planar neuromuscular control of the core during a task requiring upper and lower extremity movements.[19] These tests are commonly used as tests within a larger screen; however, their utility and validity as stand-alone tests of core stability are unknown.

Lab-based measures designed to assess the neuromuscular control aspect of core stability have been developed for the purpose of identifying trunk neuromuscular control impairments in patients with low back pain.[21-23] These measures use seated balance tasks that isolate core neuromuscular control by minimizing influence from the upper and lower extremities. The variables associated with these measures provide quantifiable data regarding an individual’s ability to control the motion and position of the trunk and pelvis during static and dynamic tasks. While these lab-based measures allow us to quantify the neuromuscular control aspect of core stability, few clinical tests have been validated against these measures. This could potentially result in inaccurate assessment and interpretation of clinical tests of core stability. The purpose of this study was to determine the construct validity of common and novel clinical tests of core stability with a focus on identifying clinical tests that emphasize assessment of core neuromuscular control in an athletic population. The authors hypothesized that clinical tests of core muscle capacity would demonstrate a small non significant correlation to the lab-based measures of core neuromuscular control while clinical tests of core neuromuscular control would moderately correlate to lab-based measures. The study attempts to determine the construct validity of clinical tests of core stability using a convergent and divergent validity approach. Convergent validity is defined as an indication two tests believed to reflect the same construct will be correlated ($r > 0.3$, $p < 0.05$).[24] Conversely, divergent validity represents the indication that no significant correlation exists between tests that are thought to reflect different constructs.[24]

METHODS

Study Design

This cross-sectional study was conducted as part of a larger research study assessing core stability in athletes with and without non-traumatic shoulder injuries. All of the athletes completed commonly used clinical measures of core stability and a lab-based test of core neuromuscular control as part of that study. Clinical tests utilized published procedures or procedures developed specifically for this study. Tests were selected based on the results of a comprehensive literature search relative to the association of core stability and athletic injuries.

Subjects

Data from eighty-one collegiate athletes were used in this study. Athletes were recruited from two Division I universities, and athletic organizations in the area through flyers, athletic trainers, coaches, and team physicians. Prior to the start of any testing procedures, all participants signed informed consent documents approved by the (blinded) University Institutional Review Board. Inclusion criteria were athletes between the ages of 18-35, with a minimum participation of 10 hours per week in practice, games, and/or strength and conditioning workouts. An athlete was defined as an individual currently competing in any sport at a professional, semi-professional, varsity, junior varsity, or club level. Subjects were excluded if they presented with any of the following: current concussion, cervical spine or lumbar spine injury, and any previous injury that still affected their ability to play their usual sport (i.e., not cleared for unrestricted participation in their usual sport by the team physician). Demographic and morphological data were collected as follows: age, sex, height in centimeters, weight in kilograms, leg length in centimeters, hand dominance/leg dominance, sport, usual sport position played, if they are in or out of season, and if their current strength and conditioning workouts including core stabilization. Physical activity levels were measured using the Baecke Sports Activity Questionnaire.

Procedures

Subjects attended one testing session and were asked to refrain from strenuous exercise 24 hours prior to the testing session to avoid potential effects of fatigue. All subjects performed lab-based measures of isolated core neuromuscular control first, followed by a five-minute rest and then completion of a battery of clinical tests. A five-minute rest was provided between the timed clinical tests (flexor endurance, extensor endurance, unilateral hip bridge endurance) and a one-minute rest was provided between all other clinical tests (active hip abduction, side bridge with active hip abduction, trunk stability push up, and rotary stability test). Test order was not randomized in order to optimize study flow within the lab space. Subjects performed each test once per instructions.

Lab-based Measures

Lab-based measures of isolated core neuromuscular control were obtained from an unstable sitting test during static and dynamic testing conditions (Figure 2a). This apparatus and test isolates core neuromuscular control by minimizing involvement of the lower extremities through use of straps and a footplate that is attached directly to the chair. The seat is attached to a solid hemisphere (44 cm diameter), which sits atop a force plate (Kistler AG, Winterthur, Switzerland). Padded safety railings surrounded the subject in the event that the subject lost balance. Details of the apparatus design and static protocol have been previously reported.[23] Isolated core neuromuscular control tests consisted of static trunk control (eyes open) and dynamic trunk control utilizing a specially designed target acquisition task (Figures 2b, 2c). Data were collected at 1600 Hz and center of pressure (CoP) measures derived from the force plate data were used to quantify control.

Static core neuromuscular control was quantified using the mean velocity of the CoP (MVEL) traveled during the static eyes open test. Subjects performed three-60s trials in which they were instructed to sit up tall with their arms across their chest, eyes open, and move as little as possible during the trial. The average of three trials was used for analysis**.** A higher mean velocity is representative of poor control of the body's center of mass, or poor core stability. This variable has been validated [25] and used to assess core neuromuscular control in patients with low back pain.[22,23,25]

The dynamic test requires an individual to move a cursor, representing their CoP, from one target to another as quickly and accurately as possible, using trunk and pelvis movements. All subjects started with the cursor at the center target. They were then asked to move the cursor toward a target (2mm diameter, 35mm away from the center target) in one of 8 directions and then return to the center target (figure 2d). Subjects completed this process until they moved the cursor to all 8 targets.. CoP measures were used to quantify dynamic core neuromuscular control using the mean velocity of the CoP during the return to the center target (DCMvel) and the 95% confidence ellipse area around the center target (PCCEA).[26,27] DCMvel represents an individual's ability to quickly return to the center target (point of balance) after they moved the cursor to a peripheral target. A slower DCMvel suggests poorer core neuromuscular control. PCCEA represents an individual's ability to accurately return to the center target after moving to a peripheral target. A higher PCCEA suggests poorer core neuromuscular control. All lab-based variables were normalized to bodyweight and trunk length as these measurements were highly correlated with performance on the lab-based measures (height – leg length) ([variable / (weight x trunk length)] x 100).

Clinical Tests of Core Stability

Subjects performed seven common clinical tests (trunk extensor endurance [TEE], flexor endurance [FE], double-leg lowering [DLTT], active hip abduction [AHA], side bridge with active hip abduction [SBAHA], rotary stability [RS], and trunk stability push up [TSPU]), and two novel clinical tests (unilateral hip bridge endurance [UHBE], and the clinical core control test [CCCT]). All subjects performed the common clinical tests. A subset of subjects performed the UHBE (n=55) and CCCT (n=52) tests. Testing procedures for these tests were developed and completed as part of a separate project while the current study was being conducted. These novel clinical tests were developed to assess the neuromuscular control aspect of core stability and were added to the current studies testing protocol.

Clinical tests of core stability were performed in the following order: CCCT, TEE, FE, DLLT, AHA, SBAHA, UHBE, RS, and TSPU. One trial of each muscle capacity test (TEE, FE, DLLT) was performed to reduce the effects of fatigue. The number of trials for all other clinical trials ranged from one to three. If the subject was able to perform the AHA, SBAHA, RS, and TSPU tests correctly without any deviations on the first or second trial, then no further trials were performed. For the UHBE and CCCT tests, the average of two trials was used for data analysis. In an attempt to ensure consistent performance on these tests the CV between the two trials to be averaged had to be less than 15%. This criterion could require subjects to perform up to three trials of each test.

Active Hip Abduction (AHA)

The active hip abduction test was performed from a side-lying position with the body in a straight line, legs placed on top of one another, and the head resting on the bottom arm (Figure 3a). From this position, subjects were instructed to abduct the top leg as far as possible while maintaining initial body position. Each side was scored on the following criteria: 0 if pain was present during movement, 1 if obvious deviations were noted, 2 if subtle deviations were noted, and 3 if no deviations were present. Deviations from expected performance include: pelvis did not remain in neutral (motion occurred in sagittal, frontal (i.e. hip hike), or transverse plane), spine did not remain neutral (motion occurred in sagittal, frontal or transverse plane), lack of symmetry in test performance between the left and right side, and/or any trunk movement prior to, during, or after active hip abduction. The average score of the two sides was used for analysis. This test has demonstrated a moderate to high intra-rater (ICC 3,1 = 0.70) and inter-rater (ICC 2,1 = 0.74) reliability.[28] Inter-rater reliability from our lab revealed fair to moderate (k = 0.34 – 0.51) agreement when assessing whether a deviation was observed and the degree of deviation.

Side Bridge with Active Hip Abduction (SBAHA)

The side bridge with active hip abduction was performed with the subject in a side-lying position propped up on their forearm (Fig 3b). With the top and bottom thighs in line with one another, subjects lifted their pelvis off the table until the head, trunk and bottom leg were in a straight line. From this position, they were instructed to raise the top leg as high as possible and then bring it back to the starting position. The average score of the two sides was used for analysis. Deviations from expected performance include: pelvis did not remain in neutral (motion occurred in sagittal, frontal (i.e. hip hike), or transverse plane), spine did not remain neutral (motion occurred in sagittal, frontal or transverse plane), lack of symmetry in test performance between the left and right side, and/or any trunk movement prior to, during, or after active hip abduction. Inter-rater reliability testing performed in our lab demonstrated slight to fair inter-rater reliability (k = 0.25 – 0.31) when assessing whether each rater observed a deviation or not. The test demonstrated slight to fair reliability (k = 0.21 – 0.26) when the amount of deviation was used to assess agreement.

Rotary Stability (RS)

Subjects performed the rotary stability test by assuming a quadruped position with the hips and knees at 90 degrees and a 2x6 board between their hands and knees. With the ankles dorsiflexed, toes, knees, and thumbs touching the board, the subject raised the arm and extended the ipsilateral hip and knee simultaneously (Figure 4a). After achieving this position, subjects brought the elevated elbow and knee towards the midline of the body to make contact above the board and then return to the starting position (Figure 4b). If unable to perform the ipsilateral pattern, subjects were allowed three attempts using a diagonal contralateral pattern (Figure 4c). This test was scored on a 0-3 scale: 0-pain with movement, 1-unable to perform the diagonal pattern, 2-unable to perform the ipsilateral pattern but able to perform the diagonal, and 3-able to perform the ipsilateral pattern. The average score of the two sides was used for analysis. RS has demonstrated perfect inter-rater agreement (k = 1.0).[29] Inter-rater reliability from our lab revealed 100% agreement (k not computable because no covariance in data) between raters when assessing whether a deviation was observed and the degree of deviation.

Trunk Stability Push-Up (TSPU)

For the trunk stability push-up, subjects assumed a prone position on the floor, feet together, knees straight, ankles dorsiflexed, and hands shoulder width apart (Figure 5A and 5B). Male subjects were required to have their thumbs in line with top of the forehead, while female subjects placed their thumbs at chin level. From this position, subjects were instructed to perform a push-up, keeping the body in a straight line. If subjects were unable to keep the body in a straight line, they were instructed to re-align the thumbs to a more proximal position, chin level for males, shoulder level for females, and the push-up was attempted again. This test was scored on a 0-3 scale: 0-pain with movement, 1-unable to perform with modification, 2-able to perform with modification, and 3-able to perform without modification. TSPU has demonstrated substantial inter-rater agreement (k = 0.75).[29] Inter-rater reliability from our lab revealed almost perfect to perfect (k = 0.89 – 1.00) agreement when assessing whether a deviation was observed and the degree of deviation.

Unilateral Hip Bridge Endurance (UHBE)

The unilateral hip bridge was performed with the subject lying supine with their arms across their chest, knees in 90 degrees of flexion, and feet flat on the table (Figure 3c). The subject performed a double-leg hip bridge, and once a neutral spine and pelvis position were achieved the subject was instructed to extend one knee (randomly determined) so their leg was straight and their thighs were parallel to one another. Subjects were instructed to hold this position as long as possible. The test was terminated when they were no longer able to maintain a neutral pelvic position as noted by 10-degree change in transverse or sagittal plane alignment. Pelvic positioning in the transverse plane was monitored by a digital inclinometer attached to a mobilization belt that was tightly secured to the individual's pelvis. A second rater visually assessed sagittal plane alignment. Two trials were performed on each side and the average of each side was used for subsequent analyses. No psychometric properties have been reported for this test.

Clinical Core Stability Test (CCCT)

The clinical core stability test required subjects to sit on either a 65 or 75cm Swiss ball with both feet off the ground for as long as possible (Figure 3d). Ball size was determined by the height of the subject. For all subjects it was essential that the size of the ball allowed both ankles to be in a neutral position (0° dorsiflexion) with the knees and hips in 90 +/- 10 degrees of flexion when the feet were on the floor. Subjects were asked to sit up tall with their arms across their chest and lift their feet from the floor while maintaining heel contact with the ball. The ball was placed 6-8 inches from the wall. A 30-second practice trial was performed where subjects were given verbal feedback, the feet were allowed to touch the ground as needed, and the ball was allowed to touch the wall behind them. Following the practice trial, two test trials were performed where the subject repeated the same procedures as the practice trial, however the test was terminated once the ball touched the wall or the feet touched the ground. Total time from when the feet were lifted from the ground to when the test was terminated was recorded. The average of two trials was used for analysis. To date, there are no psychometric properties reported for this test.

Trunk Extensor Endurance Test (TEE)

The trunk extensor endurance test (Figure 1a) required subjects to maintain neutral spine alignment during a sustained extension task. Subjects were positioned prone on a plinth with the iliac crests at the edge of the table and their upper trunk hanging down from the edge of the table. Mobilization belts secured subjects to the table at the buttocks, thigh, and ankle. Subjects were instructed to place their arms across their chest and raise their torso until it was parallel to the floor. A tester then placed a digital inclinometer on the subjects' back between their shoulder blades, the subject was told to hold this position for as long as possible, and the amount of time the position could be maintained was recorded via a stopwatch. The test was terminated when the trunk angle changed 10° from the start position or the subject stopped on their own volition. The extensor endurance test has reported inter-rater reliability of ICC 2,1 = 0.59.[30]

Flexor Endurance Test (FE)

The flexor endurance test (Figure 1b) required subjects to maintain a position similar to the top position of a sit up for as long as possible. Subjects assumed a hooklying position with the arms across the chest and a 60-degree wedge in contact with their back. Once in position, the tester moved the wedge posteriorly so there was a small gap between the subject's back and the wedge. The time was recorded from when the wedge was moved until the subject changed their hip flexion angle indicated by pressing into or moving away from the wedge. The flexor endurance test has reported intra-rater reliability of $ICC_{3,1}$ = 0.95 and inter-rater of $ICC_{2,1}$ = 0.97.[31]

Double Leg Lowering Test (DLLT)

The DLLT (Figure 1c) assesses an individual's ability to control the position of the trunk and pelvis while lowering their legs from 90° of hip flexion. Subjects were positioned supine with a blood pressure cuff under their lumbar spine. Their hips were in 90° of flexion and knees were in full extension. The examiner held the subjects' lower extremities in this position while the blood pressure cuff was inflated to 40 mmHg. The subject was then instructed to slowly lower their legs while maintaining the position of their pelvis. The test was terminated, and the degree of hip flexion (as measured by a wall goniometer) was recorded when the reading on the blood pressure cuff changed by 10 mmHg. The DLTT has reported intra-rater and test-retest reliability ($ICC_{3,1}$= 0.98) [32] and ($ICC_{2,1}$=0.63), respectively.[33]

After each test, perceived exertion was assessed via the Borg scale. If any test resulted in a rating of >13/20, the subject was allowed additional rest until the rating reached < or = 8/20 before they were allowed to continue. Forty of the subjects in this study had a current episode of shoulder pain, as this study was part of a larger study assessing the relationship between non-traumatic shoulder injuries and core stability in athletes. None of the subjects with shoulder pain performed the CKCUEST. Furthermore, all subjects completed a pain rating scale (/10 points) after each test. If any test caused a 2-point increase on the pain rating scale, the session was terminated. All subjects completed the testing protocol without any reported increased pain.

Data Analysis

Statistical analyses were conducted using Statistical Package for the Social Sciences (version 22.0; SPSS Inc, Chicago, IL). The p-value for statistical significance was set at ≤ 0.05. Descriptive data included gender, age, height, weight, sport, and hours per week of physical activity (Baecke questionnaire). Construct validity was examined using a priori hypotheses (Table 2). Convergent and divergent validity hypotheses were developed to investigate the relationships between clinical core stability tests that focused on neuromuscular control (AHA, SBAHA, TSPU, RS, UHBE, CCCT), core stability tests that focused on muscle capacity (EXT, FLEX, DLLT), and lab-based measures of core neuromuscular control. The authors hypothesized that there would be at least a moderate correlation (0.3 or greater) with clinical tests that emphasized neuromuscular control (convergent validity) and little to no correlation (less than 0.3) with clinical tests that emphasized muscle capacity (divergent validity) when correlated to the lab-measures of core neuromuscular control. Pearson correlations were used to examine these relationships for normally distributed data. For data that were not normally distributed, Spearman's rho was used. Correlations were interpreted according to Cohen [0.1-small, 0.3-moderate, 0.5-large].[34] Values greater than 3 standard deviations from the mean were removed prior to analysis. A minimum of two out of the three hypotheses needed to be supported in order for a test to demonstrate construct validity. A priori power analysis (G*Power 3) suggested a sample size of 67 to detect a moderate effect size, r = 0.3, (power = .80; alpha .05).[35,36]

RESULTS

Subject characteristics are presented in Table 1. The average Baecke score for all subjects was 6.1 ± 1.1. All athletes, except one, were considered as participants in medium to high intensity sports according to the Baecke scale. Descriptive statistics for clinical and lab-based measures are reported in Table 3. There was a significant difference in UHBE performance between the left and right sides ($t = -2.7$, $p = 0.01$); therefore, sides were analyzed separately. None of the clinical tests of neuromuscular control were moderately correlated with the lab-based measures. However, four of the clinical tests of neuromuscular control had a small significant correlation with the lab-based neuromuscular control variables: SBAHA and PCCEA ($r_s = -0.24$, $p = 0.04$), TSPU and DCMVEL ($r_s = -0.23$, $p = 0.02$), RS and PCCEA ($r_s = -0.22$, $p = 0.05$), and CCCT and DCMVEL ($r_s = 0.27$, $p = 0.05$). There were small significant correlations between the clinical tests of muscle capacity and lab-based neuromuscular control variables: EXT and DCMVEL ($r_s = 0.22$, $p = 0.03$), and FLEX and PCCEA ($r_s = -0.21$, $p = 0.03$). Results for all correlations are listed in Table 4.

DISCUSSION

The purpose of this study was to determine the construct validity of common and novel clinical tests of core stability using a convergent and divergent validity approach. None of the clinical measures of core stability emphasizing neuromuscular control demonstrated acceptable convergent validity (0.3 or greater correlation to the lab-based measure of neuromuscular control). A priori, we considered any correlation greater than or equal to 0.3, a medium or moderate effect according to Cohen[35], as a clinically important relationship. A correlation of 0.3 or greater represents 9% of the variance in the lab-based variables of isolated core stability. It was hypothesized that trunk flexor, trunk extensor endurance, and double-leg lowering tests would demonstrate small correlations with the lab-based measures because it is assumed that the lab measures are primarily assessing neuromuscular control while these clinical tests assess core muscle capacity. Our hypotheses were confirmed (2/3 – 3/3), as these three tests had correlational values less than 0.3 (divergent validity), which suggests that they are primarily assessing a different construct than the lab measures.

There was a small significant correlation between the clinical core control test (CCCT) and DCMVEL. Data revealed that the CCCT explained approximately 7% of the variance in DCMVEL. While the CCCT was designed as a clinical version of the lab-based test used in the current study, it appears that the CCCT may not be an adequate clinical assessment of the neuromuscular control aspect of core stability in athletes. The lack of a moderate correlation between the lab-based measures and the CCCT may be explained by the influence of bodyweight and height of the individual on CCCT performance. The ball deforms based on bodyweight, creating a larger surface area in contact with the ground, thus changing the demands of the task. While in the lab measures, the surface area of the chair to the force plate remains constant between subjects. Trunk length and leg length may have also affected performance on the ball based on an individual's mass distribution. Individuals with longer trunk lengths have a higher center of mass, which may increase the challenge of the task. However, this challenge should be similar between the clinical and lab measures. Leg length may have influenced performance, as individuals with longer legs may have had to assume a more flexed hip position. This may have resulted in the trunk and/or pelvis being out of a neutral position, potentially making it more challenging for a subject to maintain their balance. This is different from the lab-based test because the set up of the lab test allows for preservation the 90-90 position of the hips and knees. Thus, anthropometric differences potentially create an opposite effect on these two tests, as the ball deformation makes the tasks easier for the clinical tests, but greater weight and trunk length on the lab test make the task harder. While the CCCT demonstrates face validity, it lacks construct validity in this sample of athletes.

We normalized lab-based measures based on the fact that there were moderate to large significant correlations (range $r_s = 0.33$ –0.67) of weight, height and trunk length to performance on the lab-based variables. Though we normalized the lab-based measures for weight and trunk length we did not normalize the results of the clinical tests. Subject height and weight did not significantly correlate with performance on most clinical tests. Only the trunk stability push up was significantly correlated to height ($r = 0.26$, $p = 0.03$) and weight ($r = 0.36$, $p = 0.001$), suggesting the characteristics may potentially affect performance of this test. However, these were small to moderate correlations (explaining less than 13% of the variance), whereas the lab-based measures demonstrated moderate to large correlations to weight, height, and trunk length.

The small significant relationships between clinical tests of neuromuscular control (SBAHA, RS, and TSPU) and the lab-based measures (PCCEA and DCMVEL) may be explained as these clinical tests require small, quick adjustments in trunk position for successful completion of the task. PCCEA represents the ability to control the position of the trunk and pelvis while DCMVEL represents the ability to quickly return to a neutral position after a perturbation. Therefore, these clinical tests may be better representations of an individual's ability to quickly and accurately return the trunk and pelvis to neutral after a perturbation when compared to the other clinical tests used in this study. However, the small significant correlations between the clinical and biomechanical tests explain only 4-5% of the variance in the lab-based measures.

Two of the clinical tests of muscle capacity (FLEX and EXT) demonstrated small significant correlations to our lab-based measures. A possible explanation for this finding may be that some amount of precision and velocity control of the trunk/pelvis is needed to make small adjustments to maintain the testing position. In an effort to maintain the clinical test position, the athlete must use proprioceptive feedback to control the position of the trunk and pelvis. Even though these relationships were statistically significant, the results do not validate these tests as primary measures of core neuromuscular control.

While some clinical tests of core stability demonstrated statistically significant correlations to our lab-based measures of isolated core neuromuscular control, no clinical test achieved the a priori definition of acceptable construct validity. This study utilized athletes 18-35 years old, and thus, these results may not be generalizable to athletes under the age of 18 or over the age of 35. The clinical tests used in this study were chosen based on expert opinion (assessed via a Delphi panel) and current evidence; however, they do not represent all possible clinical assessments of core stability. Certain clinical tests used (AHA, SBAHA, RS, and TSPU) were scored on a 0-3 ordinal scale; therefore a small range of possible scores combined with similar performance across subjects may have influenced the correlations.

CONCLUSIONS

No common or novel clinical test of core stability individually demonstrated acceptable construct validity for assessing the neuromuscular control aspect of core stability in an athletic population. Our findings suggest that clinical tests used in this study are measuring constructs different than that of lab-based measures of isolated core neuromuscular control. Future work should be done to better understand the utility of these clinical tests in athletes as well as the development of valid clinical tests of isolated core neuromuscular control.

Table 1. Subject Characteristics (mean ± standard deviation)

Subject Characteristics					
Sex	**N**	**Age (years)**	**Height (cm)**	**Weight (kg)**	**Weekly Activity (hours)**
Females	25	21.8 ± 3.9	168.2 ± 8.6	68.1 ± 12.4	16.9 ± 5.9
Males	55	20.9 ± 3.0	179.8 ± 7.7	92.0 ± 17.4	19.8 ± 6.2

Table 2. A Priori Hypotheses

	A Priori Hypotheses								
	Neuromuscular Control						Muscle Capacity		
	CCCT	UHBE	RS	TSPU	AHA	SB AHA	DLLT	TEE	FLEX
Hypothesis									
1. Correlation of 0.3 or greater b/w clinical measure and MVEL	+	+	-	+	+	+	-	-	-
2. Correlation of 0.3 or greater b/w clinical measure and DCMVEL	+	+	+	+	+	+	-	-	-
3. Correlation of 0.3 or greater b/w clinical measure and PCCEA	+	+	+	-	+	+	+	-	-
Hypothesis confirmed:	0/3	0/3	1/3	1/3	0/3	0/3	2/3	3/3	3/3

* + Indicates that the clinical test will be correlated at 0.3 or higher with the lab measure.
- Indicates that the clinical test will not reach a correlation of 0.3 with the lab measure.
Abbreviations: Abbreviations: CCCT: Clinical core stability test; TEE: Trunk extensor endurance test; FLEX: Trunk flexor endurance test; DLLT: Double leg lowering test; AHA: Active hip abduction test; SBAHA: Side bridge with active hip abduction; UHBE L: Unilateral hip bridge endurance test, left side; UHBE R: Unilateral hip bridge endurance test, right side; RS: Rotary stability; TSPU: Trunk stability push up; MVEL: Static mean velocity of center of pressure normalized to bodyweight and head arm trunk length; DCMVEL: Dynamic mean velocity of center of pressure during target test normalized to bodyweight and head arm trunk length; PCCEA: 95% confidence ellipse area of center of pressure during target test normalized to bodyweight and head arm trunk length.

Table 3. Descriptive Statistics of Clinical and Lab-Based Measures

Test	N*	Mean	SD
CCCT (s)	52	59.80	71.60
EXT (s)	77	77.15	29.97
FLEX (s)	78	94.59	39.09
UHBE L (s)	55	19.56	16.51
UHBE R (s)	55	25.55	21.12
DLLT (degrees)	80	21.88	16.62
AHA (0-3)	80	2.24	0.85
SBAHA (0-3)	80	2.25	1.09
RS (0-3)	80	2.08	0.73
TSPU (0-3)	80	2.46	1.06
MVEL (mm/s)	79	0.07	0.03
DCMVEL (mm/s)	79	0.38	0.14
PCCEA (mm^2)	79	1.41	0.54

Abbreviations: CCCT: Clinical core stability test; TEE: Trunk extensor endurance test; FLEX: Trunk flexor endurance test; DLLT: Double leg lowering test; AHA: Active hip abduction test; SBAHA: Side bridge with active hip abduction; UHBE L: Unilateral hip bridge endurance test, left side; UHBE R: Unilateral hip bridge endurance test, right side; RS: Rotary stability; TSPU: Trunk stability push up; MVEL: Static mean velocity of center of pressure normalized to bodyweight and head arm trunk length; DCMVEL: Dynamic mean velocity of center of pressure during target test normalized to bodyweight and head arm trunk length; PCCEA: 95% confidence ellipse area of center of pressure during target test normalized to bodyweight and head arm trunk length.
*N represents sample size after outliers were removed.

Table 4. Relationships between clinical tests and lab-based measures of core stability

	Lab-Based Measures		
Clinical Test	**Static**	**Dynamic**	
	MVEL	**DCMVEL**	**PCCEA**
CCCT	0.00	***0.27***	-0.03
UHBE_L	-0.11	0.04	0.06
UHBE_R	0.06	0.15	0.00
AHA	0.13	-0.02	-0.17
SBAHA	0.04	-0.06	***-0.24***
RS	-0.04	0.01	***-0.22***
TSPU	-0.16	***-0.23***	-0.09
FLEX	-0.14	0.18	***-0.21***
EXT	-0.11	***0.22***	0.01
DLLT	-0.15	0.04	-0.02

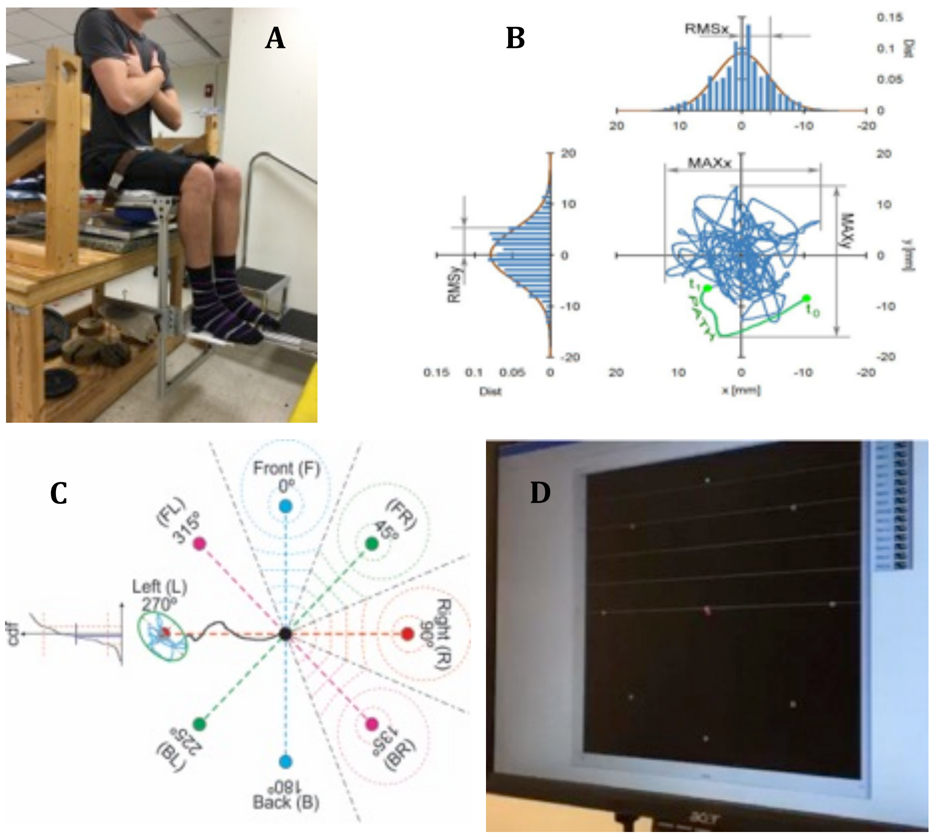
Bold italics indicates significance at $p < 0.05$.

Abbreviations: CCCT: Clinical core stability test; TEE: Trunk extensor endurance test; FLEX: Trunk flexor endurance test; DLLT: Double leg lowering test; AHA: Active hip abduction test; SBAHA: Side bridge with active hip abduction test; UHBE L: Unilateral hip bridge endurance test, left side; UHBE R: Unilateral hip bridge endurance test, right side; RS: Rotary stability; TSPU: Trunk stability push up; MVEL: Static mean velocity of center of pressure normalized to bodyweight and head arm trunk length; DCMVEL: Dynamic mean velocity of center of pressure during target test normalized to bodyweight and head arm trunk length; PCCEA: 95% confidence ellipse area of center of pressure during target test normalized to bodyweight and head arm trunk length.

Figure 1. Clinical tests of core muscle capacity.

A) Trunk extensor endurance (EXT) requires an individual to maintain neutral trunk position for a maximum amount of time. B) Trunk flexor endurance (FLEX) requires an individual to maintain approximately 60 degrees of hip flexion for a maximum amount of time. C) Double-leg lowering test (DLLT) requires the individual to lower the legs in a slow and controlled manner while not changing the pressure in the sphygmomanometer under the lumbar spine.

Figure 2. Lab-based measure of isolated core neuromuscular control.

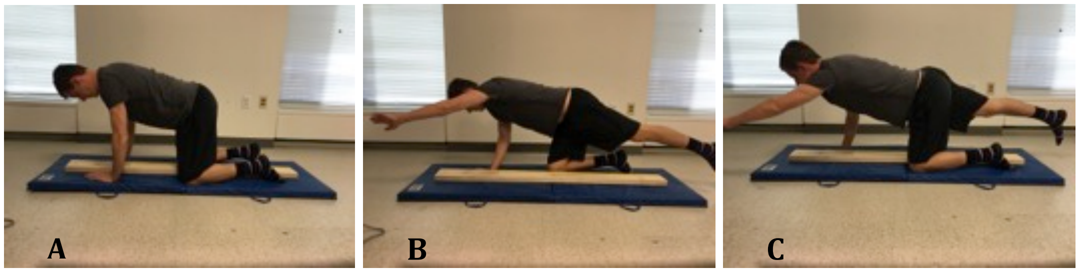


A) Subject set up on chair: this setup reduces influence of the lower extremities by strapping the legs together and supporting the feet on a footplate that is attached to the chair thus eliminating control of the chair through the lower extremities. B) COP information from force plate data allow us to quantify performance using the 95% confidence ellipse area and mean velocity of the center pressure during static balance. C) This is an illustration of the target acquisition test orientation and directional control variables associated with the test. Directional control is measured by the excursion of the COP to and from the target and the amount of movement around the target. D) A computer monitored is positioned directly in front of subjects for the target test.

Figure 3. Clinical Tests of core neuromuscular control

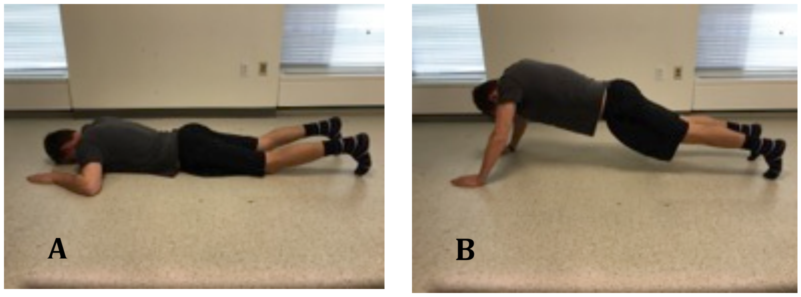
A) The active hip abduction test requires frontal plane control of the lumbopelvic complex. B) The side bridge with active hip abduction test challenges frontal plane stability and control of the lumbopelvic complex and shoulder during active movement of the lower extremity. C) The unilateral hip bridge endurance test challenges transverse and sagittal plane neuromuscular control of the lumbopelvic complex. D) The core control clinical test is modeled as a clinical version of the lab-based measure in the current study. Individuals balance on a 75cm Swiss ball without allowing the feet to touch the ground or the ball to touch the wall.

Figure 4. Functional Movement Screen core stability tests



A) Subjects assume a quadruped position straddling a 2x6 board as the start position of the rotary stability test. B) The ipsilateral pattern of the rotary stability test requires individuals to extend the arm and leg on the ipsilateral side, bring the elbow and knee into contact above the board, and then return to the start position C) The diagonal pattern of the rotary stability test requires individuals to extend the arm and leg on the contralateral side, bring the elbow and knee into contact above the board, and then return to the start position.

Figure 5. Trunk Stability Push-Up (TSPU)



A) Starting position of the trunk stability push-up: thumbs are in line with the forehead, hands outside of the shoulders, and toes pulled towards the shin. B) Finishing position of the trunk stability push-up: body lifts as one unit into the top position of a push-up.

REFERENCES

1. Conn JM, Annest JL, Gilchrist J. Sports and recreation related injury episodes in the US population, 1997-99. *Inj Prev.* Jun 2003;9(2):117-123.

2. Burt CW, Overpeck MD. Emergency visits for sports-related injuries. *Ann Emerg Med.* Mar 2001;37(3):301-308.

3. Dick R, Agel J, Marshall SW. National Collegiate Athletic Association Injury Surveillance System commentaries: introduction and methods. *J Athl Train.* Apr-Jun 2007;42(2):173-182.

4. Hootman JM, Dick R, Agel J. Epidemiology of collegiate injuries for 15 sports: summary and recommendations for injury prevention initiatives. *J Athl Train.* Apr-Jun 2007;42(2):311-319.

5. Cholewicki J, Silfies SP, Shah RA, et al. Delayed trunk muscle reflex responses increase the risk of low back injuries. *Spine (Phila Pa 1976).* Dec 1 2005;30(23):2614-2620.

6. Ireland ML, Willson JD, Ballantyne BT, et al. Hip strength in females with and without patellofemoral pain. *J Orthop Sports Phys Ther.* Nov 2003;33(11):671-676.

7. Zazulak BT, Hewett TE, Reeves NP, et al. Deficits in neuromuscular control of the trunk predict knee injury risk: a prospective biomechanical-epidemiologic study. *Am J Sports Med.* Jul 2007;35(7):1123-1130.

8. Zazulak BT, Hewett TE, Reeves NP, et al. The effects of core proprioception on knee injury: a prospective biomechanical-epidemiological study. *Am J Sports Med.* Mar 2007;35(3):368-373.

9. Willardson JM. Core stability training: applications to sports conditioning programs. *J Strength Cond Res.* Aug 2007;21(3):979-985.

10. Kibler WB, Press J, Sciascia A. The role of core stability in athletic function. *Sports Med.* 2006;36(3):189-198.

11. Silfies SP, Ebaugh D, Pontillo M, et al. Critical review of the impact of core stability on upper extremity athletic injury and performance. *Braz J Phys Ther.* Sep-Oct 2015;19(5):360-368.

12. Zazulak B, Cholewicki J, Reeves NP. Neuromuscular control of trunk stability: clinical implications for sports injury prevention. *J Am Acad Orthop Surg.* Sep 2008;16(9):497-505.

13. Alaranta H, Luoto S, Heliovaara M, et al. Static back endurance and the risk of low-back pain. *Clin Biomech (Bristol, Avon).* Sep 1995;10(6):323-324.

14. Tate A, Turner GN, Knab SE, et al. Risk factors associated with shoulder pain and disability across the lifespan of competitive swimmers. *J Athl Train.* Mar-Apr 2012;47(2):149-158.

15. Nelson-Wong E, Flynn T, Callaghan JP. Development of active hip abduction as a screening test for identifying occupational low back pain. *J Orthop Sports Phys Ther.* Sep 2009;39(9):649-657.

16. McKeown I, Taylor-McKeown K, Woods C, et al. Athletic ability assessment: a movement assessment protocol for athletes. *Int J Sports Phys Ther.* Dec 2014;9(7):862-873.

17. Okubo Y, Kaneoka K, Imai A, et al. Electromyographic analysis of transversus abdominis and lumbar multifidus using wire electrodes during lumbar stabilization exercises. *J Orthop Sports Phys Ther.* Nov 2010;40(11):743-750.

18. Butowicz CM, Ebaugh DD, Noehren B, et al. Validation of Two Clinical Measures of Core Stability. *Int J Sports Phys Ther.* Feb 2016;11(1):15-23.

19. Cook G, Burton L, Hoogenboom BJ, et al. Functional movement screening: the use of fundamental movements as an assessment of function-part 2. *Int J Sports Phys Ther.* Aug 2014;9(4):549-563.

20. Cook G, Burton L, Hoogenboom BJ, et al. Functional movement screening: the use of fundamental movements as an assessment of function - part 1. *Int J Sports Phys Ther.* May 2014;9(3):396-409.

21. Cholewicki J, Simons AP, Radebold A. Effects of external trunk loads on lumbar spine stability. *J Biomech.* Nov 2000;33(11):1377-1385.

22. Radebold A, Cholewicki J, Polzhofer GK, et al. Impaired postural control of the lumbar spine is associated with delayed muscle response times in patients with chronic idiopathic low back pain. *Spine (Phila Pa 1976).* Apr 1 2001;26(7):724-730.

23. Sung W, Abraham M, Plastaras C, et al. Trunk motor control deficits in acute and subacute low back pain are not associated with pain or fear of movement. *Spine J.* Aug 1 2015;15(8):1772-1782.

24. Portney LG, Watkins MP. *Foundations of Clinical Research: Applications to Research.* Third Edition ed. New Jersey: Pearson Education, Inc.; 2009.

25. Silfies SP, Cholewicki J, Radebold A. The effects of visual input on postural control of the lumbar spine in unstable sitting. *Hum Mov Sci.* Aug 2003;22(3):237-252.

26. Sung W, Wattananon P, Spinelli B, et al. Identification of Dynamic Trunk Movement Control Impairments in Patients with Non Specific Low Back Pain Using a Novel Target Acquisition Test. Paper presented at: 7th World Congress of Biomechanics, 2014; Boston, MA.

27. Butowicz CM, Pontillo M, Milner CE, et al. Differences In Core Stability Between Collegiate Football Players With And Without Shoulder Pain. *Med Sci Sports Exerc.* 2016;In press.

28. Davis AM, Bridge P, Miller J, et al. Interrater and intrarater reliability of the active hip abduction test. *J Orthop Sports Phys Ther.* Dec 2011;41(12):953-960.

29. Onate JA, Dewey T, Kollock RO, et al. Real-time intersession and interrater reliability of the functional movement screen. *J Strength Cond Res.* Feb 2012;26(2):408-415.

30. Moreland J, Finch E, Stratford P, et al. Interrater reliability of six tests of trunk muscle function and endurance. *J Orthop Sports Phys Ther.* Oct 1997;26(4):200-208.

31. Evans K, Refshauge KM, Adams R. Trunk muscle endurance tests: reliability, and gender differences in athletes. *J Sci Med Sport.* Dec 2007;10(6):447-455.

32. Krause DA, Youdas JW, Hollman JH, et al. Abdominal muscle performance as measured by the double leg-lowering test. *Arch Phys Med Rehabil.* Jul 2005;86(7):1345-1348.

33. Lanning CL, Uhl TL, Ingram CL, et al. Baseline values of trunk endurance and hip strength in collegiate athletes. *J Athl Train.* Oct-Dec 2006;41(4):427-434.

34. Cohen J. *Statistical Power Analysis for the Behavioral Sciences.* New Jersey: Lawrence Erlbaum Associates, Inc.; 1988.

35. Cohen J. A power primer. *Psychol Bull.* Jul 1992;112(1):155-159.

36. Faul F, Erdfelder E, Lang AG, et al. G*Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behav Res Methods.* May 2007;39(2):175-191.

CHAPTER THREE: CONSTRUCT VALIDITY AND RELIABILITY OF A NOVEL COMPREHENSIVE MOVEMENT SYSTEM-SCREENING TOOL

Courtney M. Butowicz, MSEd, CSCS[1]; D. David Ebaugh, PhD, PT[1,2]; Marisa Pontillo, PT, DPT, SCS[1,3]; Sheri P. Silfies. PhD, PT[1]

[1] Physical Therapy & Rehabilitation Sciences Department, Drexel University, Philadelphia, PA, USA

[2] Health Sciences Department, Drexel University, Philadelphia, PA, USA

[3] GSPP Penn Therapy and Fitness at Penn Sports Medicine Center, Philadelphia, PA, USA

Correspondence: Address all correspondence to Sheri P. Silfies, PT, PhD, Drexel University, Rehabilitation Sciences Spine Research Laboratory, Three Parkway, Mail Stop 7-502, Philadelphia, PA 19102-1192, USA. Tel: (267) 359-5580; Fax: (267) 359-5576.
Email: silfies@drexel.edu

Statement of Support: This work was supported in part by The American Physical Therapy Association, Sports Section Legacy Fund.

ABSTRACT

Background: Non-traumatic shoulder injuries will affect nearly a third of all overhead athletes and account for nearly three quarters of the time lost to injury in some sports. Proposed risk factors for decreased performance and injury risk include movement pattern inefficiency, decreased regional stability, decreased mobility, and asymmetrical movement. In order to comprehensively evaluate the movement system, pre-participation screens should assess all of the aforementioned risk factors or constructs.

Purpose/Hypothesis: The purpose of the current study was to determine the construct validity, item inter-rater reliability, and composite score inter-rater reliability of the movement system screening tool (MSST) which is a novel comprehensive screening tool for athletes.

Study Design: Cross-Sectional design

Methods: Eighty-one collegiate athletes completed 34 clinical tests that comprise the MSST. Exploratory factor analysis (EFA) was performed to identify constructs within the MSST. Inter-rater reliability was determined for individual test and composite scores, from two independent, experienced raters.

Results: EFA revealed three of the four design constructs over 7 factors, representing 63% of the variance accounted for within the MSST: movement pattern efficiency (lower extremity, dynamic lower extremity), regional stability (upper and lower extremity, trunk/pelvis, dynamic), and mobility (upper and lower extremity, trunk/pelvis). Individual test inter-rater reliability ranged from fair to perfect (κ= 0.26 – 1.00). Inter-rater reliability of the MSST composite score was excellent, ICC (2,1) = 0.94, 95% CI (0.91, 0.96).

Conclusions: Exploratory factor analysis revealed 7 factors within the MSST, representing the overall constructs of movement pattern efficiency, regional stability, and mobility. Inter-rater reliability of test-items and composite score of the MSST is promising. The results of the current study suggest the MSST may have adequate reliability and validity for use in clinical settings. However, future work should be done to assess the test-retest reliability and predictive validity of the MSST.

Levels of Evidence: Level III

Keywords: athletic injuries, screening, movement system

INTRODUCTION

Over 10,000 people in the United States seek medical care for musculoskeletal injuries sustained during sports, exercise, or recreational activities daily.[1] Serious upper and lower extremity injuries are common in sports such as basketball, baseball, softball, volleyball, soccer, lacrosse, swimming, and field hockey. Anterior cruciate ligament injuries alone cost over $850 million in surgical costs each year, with another $2 billion spent on rehabilitation.[2] Non-traumatic shoulder injuries, such as rotator cuff tendinitis and shoulder impingement syndrome, will affect nearly 30% of all overhead athletes (e.g., baseball, tennis athletes).[3] Upper extremity injuries account for nearly 75% of the time lost to injury in collegiate baseball players, with 69% of these injuries seen in pitchers.[4] Along with the high cost of treatment, injuries can lead to the loss of competition seasons, scholarship funding, decreased academic performance, long-term disability, and increased risk of osteoarthritis later in life.[5]

Musculoskeletal injuries also affect U.S. military personnel and first responders, and are a leading cause of disability in the armed services. In active duty personnel, 90% of all musculoskeletal injuries result from physical training and sports activities.[6-11] Five hundred forty-eight million dollars in patient care costs were the direct result of approximately 2.4 million medical visits made to military medical treatment facilities as a result of musculoskeletal injuries in 2007.[12] Annually, there are more than 11 million limited duty days due to musculoskeletal injuries, with lower extremity injuries accounting for 4.8 million of these injuries.[13]

Risk factors proposed to decrease performance and increase injury risk include movement pattern inefficiency, decreased regional stability (i.e. core stability), decreased mobility, and asymmetrical movement.[14-25] There is emerging evidence linking poor core stability to upper and lower extremity and low back injury in athletes.[16,17,26-30] Core stability is defined as the ability to control the motion, position, and stiffness of the trunk and pelvis relative to the extremities in order for optimal transfer, generation, and dissipation of force through the kinetic chain.[31] Regional stability may directly affect movement pattern efficiency. Movement pattern efficiency is defined as the coordination of motion (timing and amount) between body segments to effectively accept, generate, or transfer forces to accomplish a skill or task. The kinetic chain model suggests the core functions as the mechanical link between body segments. This allows for the sequential coordination of segments to efficiently generate and transfer forces throughout the body.[32] Many movements in sports require force transfer from the hips and trunk to the upper extremities. Coordinated muscular activity through the core (trunk, pelvis, hip) is necessary for this sequence of force transfer between segments. The inability to produce, transfer, and dissipate forces effectively can lead to increased loads on the extremities, increasing the potential for injury.[31,33] Identifying deficits in stability, mobility, and movement symmetry are critical because of their influence on movement pattern efficiency.[34]

Pre-participation screens proposed to assess movement patterns and athletic performance capabilities include the Functional Movement Screen (FMS), 16-item physical performance measure screening battery (16-PPM), and Athletic Ability Assessment (AAA).[34-36] These screens use multi-segment movements to assess key movement patterns and identify breakdowns within the kinetic chain.[24,35-38] The 16-PPM and AAA are relatively new screening tools that have been introduced within the last two years. The 16-PPM has reported individual item test-retest reliability ranging from ICC 0.05-0.88 for quantitative measures, and k_w 0.32-0.81 for qualitative measures.[36] Item inter-rater reliability of the 16-PPM ranged from ICC 0.03-0.99 for quantitative measures, and k_w 0.24-0.93 for qualitative measures. The AAA has very good inter-rater reliability (ICC = 0.96, 95% CI: 0.94-0.98) for the composite score. While reliability values for the 16-PPM and AAA have been reported no evidence of predictive or construct validity for either screening tool has been reported. This significantly limits the clinical usefulness of these two screens. The FMS appears to be the most popular pre-participation screen. Test-retest reliability of the FMS composite score for a single rater has been reported to be good to excellent (ICC = 0.6 – 0.92).[39] Test-item inter-rater reliability was reported as substantial to excellent (kappa = 0.74-1.0, ICC = 0.92 – 0.98) when using novice and expert raters.[38,40] There is conflicting evidence with regards to the predictive validity of the FMS.[41-45] FMS developers caution against using the composite score to predict injury risk as the intent of the screen was to identify functional limitations in movement patterns before beginning a new fitness program or at the end of rehabilitation.[46] Screen developers suggest this information could be used to identify a "movement baseline" from which injury prevention interventions could be developed.[46] Of the three screens discussed, the 16-PPM is the only screen with multiple upper extremity assessments (including stability and mobility) and that also directly assesses multi-planar core stability. Therefore, there is a need for a valid and reliable pre-participation screen designed to predict injury based on proposed injury risk factors.

Secondary to the long-term effects of, and costs associated with musculoskeletal injuries, there is an increased interest in the ability to predict these injuries in athletic and military populations. In order to comprehensively evaluate the movement system pre-participation screens should assess all of the aforementioned risk factors. Using the kinetic chain model as the framework for a comprehensive screen, movement pattern efficiency, regional stability, mobility, and symmetry of motion are considered important constructs for the foundation of human movement. Alterations within these constructs may directly affect movement, mechanics, and/or ultimately performance of highly demanding physical activities and may place individuals at risk for injury.

While it is important to comprehensively assess each of the risk factors listed, pre-participation screens must be succinct and efficient. Pragmatically, movement system screens must be easy to administer, require minimal equipment, and time-efficient for implementation into large scale screening procedures.[38] In this study, the authors propose a novel screen to assess the movement system in athletes. The Movement System Screening Tool (MSST) was designed to assess movement pattern efficiency, regional stability, mobility, and movement symmetry in the upper and lower extremities and the core. The purposes of this study were to: 1) describe the development of the MSST, 2) determine the construct validity of the MSST, and 3) determine individual test inter-rater reliability and composite score inter-rater reliability of the MSST.

METHODS

Study Design

Tests with injury predictive capabilities, and tests that are commonly used in orthopedic assessments were selected from the current literature to generate the group of tests upon which the initial version of the MSST was based. A Delphi approach was then used to assess the content validity of the initial version of the MSST. A cross-sectional design was used to assess construct validity, reduce the overall number of tests, and assess inter-rater reliability of each test as well as the inter-rater reliability of the composite MSST score.

Movement System Screening Tool Development

For the Delphi approach, an expert panel of experienced physical therapists with sports and orthopedic specialty certifications, athletic trainers, certified strength and conditioning specialists, and sports biomechanists determined the *content validity* of the initial version of the MSST. Three rounds of analyses were used to determine agreement upon the screen constructs, test assessment of body regions, test performance characteristics, value of symmetrical performance, and finally value of test inclusion in the screen. New screening tests were developed and validated for constructs in which the expert panel identified a gap in the literature.[47] The end result of this process was the identification of 21 different tests (13 tested bilaterally), from the initial group of 33, to be included in the MSST (see Table 1). These tests were proposed to assess movement pattern efficiency, stability, mobility, and movement symmetry in the core, upper, and lower extremities.

Subjects

Data from eighty-one collegiate and professional athletes were used to determine the construct validity and reliability of the MSST. Athletes were recruited from two Division I universities and athletic organizations in the area through flyers, athletic trainers, coaches, and team physicians. Prior to the start of any testing procedures, all participants signed informed consent documents approved by the (blinded) University Institutional Review Board. Inclusion criteria were athletes between the ages of 18-35, with a minimum participation of 10 hours per week in practice, games, and/or strength and conditioning workouts. An athlete was defined as an individual currently competing in any sport at a professional, semi-professional, varsity, junior varsity, or club level. Subjects were excluded if they presented with any of the following: current concussion, cervical spine or lumbar spine injury, and any previous injury that still affected their ability to play their usual sport (i.e., not cleared for unrestricted participation in their usual sport by the team physician). Demographic and morphological data were collected as follows: age, sex, height in centimeters, weight in kilograms, leg length in centimeters, hand dominance/leg dominance, sport, usual sport position played, if they are in or out of season, and if their current strength and conditioning workouts including core stabilization. Physical activity levels were measured using the Baecke Sports Activity Questionnaire. Subject characteristics are presented in Tables 2 and 3.

Procedures

Subjects attended one session and were asked to refrain from strenuous exercise 24 hours prior to the test session to avoid potential effects of fatigue. Height, weight, leg length, leg and arm dominance, hours of activity per week, and sport data were collected followed by the battery of MSST clinical tests. Test order was not randomized in order to optimize the flow of the study within the lab space. Subjects performed each test per the MSST instructions (Table 1).

After each test, perceived exertion was assessed via the Borg scale. If any test resulted in a rating of >13/20, the subject was allowed additional rest until the rating reached < or = 8/20 before they were allowed to continue. This was done in an effort to reduce the effects of fatigue, as the screen was part of a larger study protocol that lasted approximately two hours. Forty of the subjects in this study had a current episode of shoulder pain, as this study was part of a larger study assessing the relationship between non-traumatic shoulder injuries and core stability in athletes. None of the subjects with shoulder pain performed the closed kinetic chain upper extremity stability test (CKCUEST). Furthermore, all subjects completed a pain rating scale (/10 points) after each test. If any test caused a 2-point increase on the pain rating scale, the session was terminated. All subjects completed the testing protocol without any reported increased pain.

Construct Validity

A primary objective of this study was to model the MSST into constructs in an effort to reduce the number of tests within the screen. An exploratory factor analysis (EFA) was used to identify construct clusters. Once the constructs were determined, the number of tests within the screen was reduced while retaining as much of the original construct information as possible. EFA is an effective tool for test item reduction and provides a mechanism for innovative variable development based on the structure of test items within the constructs.[48]

Inter-rater Reliability

Two raters independently assessed each subject's performance on the MSST. Raters included an exercise scientist (one of the screen developers) and a physical therapist with a Sports Specialist Certification. Prior to the data collection sessions, the second rater was trained in the MSST. This session included recordings of subjects performing some of the MSST tests, as well as in person performances of some of the tests. For all data collection sessions the primary rater read the test instructions to the subjects. For those tests that required a quantitative measurement, the primary rater took the measurement and the secondary rater confirmed the measured value. Detailed descriptions of MSST test performance and how the tests were to be scored are presented in Table 1.

Inter-rater reliability was not performed on all tests. Tests that could be scored by both raters concurrently (i.e. squat) were used to assess inter-rater reliability. Tests that would have required the subject to repeat the test performance (i.e. Y-Balance Test) were not included in this analysis due to time constraints. As previously mentioned, the MSST tests were part of a larger study protocol that lasted about two hours.

Statistical Analysis

Construct Validity & Test Item Reduction

Prior to the EFA test items were analyzed for multicollinearity and missing data. Randomly missing data were imputed using single imputation while non-randomly missing data were imputed using multiple imputations. The average of five imputations was used to derive data points for non-randomly missing data. Tests were examined for factor analysis appropriateness via the Kaplin-Meyer-Olkin (KMO) measure of sampling adequacy, Bartlett's test of sphericity, and the anti-image correlation matrix. KMO and Bartlett's test of sphericity were used to determine if there was an adequate number of tests for each factor, and assessed whether the original tests were sufficiently correlated, respectively. The overall KMO statistic should be above 0.5 while Bartlett's test of sphericity should be significant at $p < 0.05$.[49] The anti-image correlation matrix displays the KMO statistic for each individual test along the diagonal of the correlation matrix. Each test should demonstrate a KMO statistic above 0.5 to be included in the analysis.[48]

Once tests with unacceptable sampling adequacy were removed, the EFA with and without factor rotation (Varimax rotation[49]) was completed. Factors with eigenvalues greater than 1.0 were extracted while test item communalities within each factor were suppressed at 0.4.[50]

Inter-rater Reliability

Inter-rater reliability was determined for those MSST tests that remained in the screen after the EFA. Cohen's kappa was used to determine inter-rater agreement for each MSST test. Inter-rater agreement of individual tests were interpreted according to Landis and Koch [<0: no agreement, 0.1-0.20: slight agreement, 0.21-0.40: fair agreement, 0.41-0.60: moderate agreement, 0.61-0.80: substantial agreement, 0.81-0.99: almost perfect agreement].[51]

For MSST composite score inter-rater reliability, each test within the MSST was scored on a 4-point scale (0-3) and summed by rater for each subject with a maximum score of 72. Intraclass correlation coefficient was used to determine inter-rater reliability of the composite score of the MSST. ICCs were interpreted according to Portney and Watkins [< 0.40: poor reliability, 0.41 – 0.74: moderate reliability, > 0.75: excellent reliability].[52] All statistical analyses were conducted using Statistical Package for the Social Sciences (version 22.0; SPSS Inc, Chicago, IL).

RESULTS

Overall, the KMO (0.58) and Bartlett's test ($p = 0.001$) revealed that 24 MSST tests were appropriate for the EFA. Examination of individual KMO statistics within the anti-image correlation matrix revealed that the following 9 tests did not have adequate sampling adequacy: left side bridge with hip abduction, modified Thomas test, left and right in-line lunge, trunk stability push up, trunk extensor endurance, trunk flexor endurance, clinical core control test, and left scapular dyskinesis and as such they were eliminated from the EFA. Thus, 24 tests were analyzed in the EFA.

The EFA revealed 7 factors (factors with Eigenvalues greater than 1.0), which represented 63% of the variance accounted for (VAF). The construct of movement pattern efficiency (MPE), representing 21.3 % VAF, loaded on two factors (lower extremity MPE with trunk/pelvis stability required and lower extremity dynamic MPE). The construct of regional stability represented 24.8% VAF loading on three factors (upper and lower extremity stability; trunk and pelvis stability; trunk and pelvis stability with extremity movement). The construct of mobility represented 16.8% VAF, loading on two factors (upper and lower extremity mobility; trunk mobility). For details see factor structure in Table 4.

Inter-rater reliability of individual MSST tests are presented in Table 5. Inter-rater reliability of the composite MSST score was ICC (2,1) = 0.94, 95% CI (0.91, 0.96).

DISCUSSION

The primary focus of this study was to determine the construct validity and inter-rater reliability of a novel comprehensive pre-participation athletic screen (MSST). Results of the EFA indicate that there are 7 factors within the MSST. These capture three constructs of the MSST (movement pattern efficiency, stability and mobility), each being represented primarily by one or two body regions: movement pattern efficiency (lower extremity, dynamic lower extremity), regional stability (upper and lower extremity, trunk/pelvis, dynamic), and mobility (upper and lower extremity, trunk/pelvis).

Combined, these 7 factors explain 62.9% of the variance in the MSST. This finding suggests that these factors represent and validate the constructs within the MSST.[54]

As part of the analysis we examined the factor structure when a Varimax rotation was applied. Varimax rotation produced 8 distinct factors, explaining 67% of the variance. The 8 factors produced represent the same constructs as the original analysis; however, the rotation further grouped some constructs by region. For example, extremity mobility became two separate factors, upper extremity mobility and lower extremity mobility. This level of detail may be useful in future work if the MSST is divided into extremity dependent subsets, such as an upper extremity screen for use in upper extremity dominant sports.

Currently, the MSST takes approximately 20 minutes to screen an individual. Optimally, we believe that screens should be completed in less than 10 minutes per person. Therefore, there may be value in the development of a subset if extremity dependent or sport specific screens. These subset screens would be established to retain the constructs of movement pattern efficiency, stability, and mobility while being expedient.

The MSST tests included tests used within other published athletic screens as well as tests based on the expert opinions. The current study investigated the test inter-rater reliability of qualitative assessments (e.g. squat) rather than quantitative assessments (e.g. single-leg hop) as the quantitative tests would have required repeat performances, which would have increased the duration of the testing protocol and likely induced subject fatigue. In addition, all quantitative tests in the MSST have established reliability, with the exception of the UHBE.[38,53-58] Individual test inter-rater reliability on the qualitative tests assessed in this study ranged from slight to almost perfect agreement (k = 0.26 – 0.97). One test demonstrating 100% agreement between raters, lacked variance in data for kappa computation. The slight agreement between raters on the side bridge with active hip abduction test may have been due to rater location. The primary raters hand was in contact with the subjects' pelvis during the task to assess off plane pelvic motion. The second rater only visually assessed all motion 1-2 meters away. The location and contact between the primary rater and the subject may provide an explanation for the lower item reliability.

Composite score inter-rater reliability was very good (ICC 2,1 = 0.94). However, this could be slightly inflated, as over half of the test items that went into the composite score were not assessed independently. However, most of the qualitative assessments reported almost perfect inter-rater agreement and the qualitative assessments used the same scoring criteria, regardless of rater.

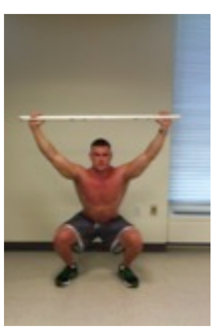
This study utilized a systematic approach to developing a comprehensive pre-participation screening tool for athletes based upon proposed risk factors for injury. The use of a Delphi technique and exploratory factor analysis to develop and validate an athletic screening tool represents an important first step to validating the tool for clinical use. This study is not without limitations. Because the screen was administered as part of a larger study, inter-rater reliability was not studied on every test within the screen. This may limit our inter-rater reliability of the composite score. However, because the tests that were not assessed by two raters have published reliability, this may mitigate this limitation. It is recommended that studies utilizing EFA typically have sample sizes of at least 100. MacCallum et al (1999) suggest that communalities in the 0.5 range should have sample sizes of at least 100; however, the minimum sample size to variable ratio depends on the study design.[59] Lawley and Maxwell (1971) suggest 51 more cases than the number of variables is acceptable in factor analysis, in which case our data meet the criteria.[60]

Several tests considered to be valuable by expert clinicians were not included in the EFA because they did not meet the statistical inclusion criteria. Removal of the modified Thomas Test may have eliminated isolated assessment of anterior lower extremity mobility. Removal of the trunk flexor and extensor endurance tests may have eliminated isolated trunk muscle capacity assessment. While these are isolated assessments of the aforementioned regions, other tests (e.g. overhead squat and unilateral hip bridge) within the screen m ay indirectly assess these constructs within these regions. To date, no test-retest reliability is available for the MSST. Therefore, the minimal detectable change and standard error are currently unknown. Future work should assess test re-test reliability as well as inter-rater reliability using raters with varying degrees of clinical experience. The scoring system of the MSST has not yet been validated. Further work needs to be done to validate the composite score and individual test-item scores. While our data achieved minimally acceptable sampling adequacy for EFA, the small sample size may have influenced factor loading. Future research efforts should include amassing a larger database of MSST scores from athletes and also expanding work to include military personnel.

CONCLUSIONS

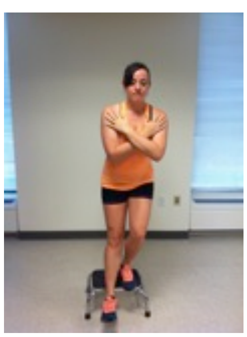
The EFA revealed 7 factors within the MSST, representing the constructs of movement pattern efficiency, regional stability, and mobility. The results of the current study suggest the MSST may be a reliable and valid screening tool for assessing the movement system. Further work needs to determine test-retest reliability as well as the predictive validity of the MSST. Identifying movement patterns or impairments that are associated with decreased performance and injury risk will allow clinicians and trainers to address these patterns directly through a neuromuscular training and injury prevention program, possibly resulting in improved performance and a reduction in injuries.[61]

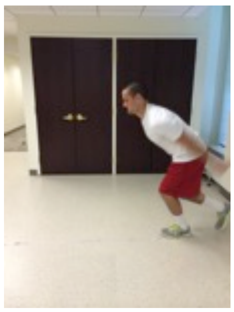
Table 1. Test items within the Movement System Screening Tool (MSST).

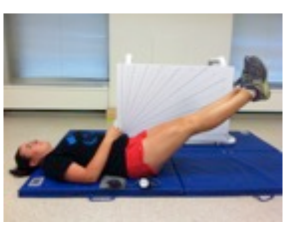
Test	Description	Scoring
Side bridge with active hip abduction 	Subject lies on their side, propped up on the forearm with the shoulder over the elbow, and the bottom knee bent to 90°. Top and bottom thighs should be inline with one another and the top leg should be straight and toes should be lifted towards the shin and pointed forward. Subject then lifts the pelvis off the floor/table until head, spine and bottom leg are in a straight line. Then they raise the top leg as high as possible.	0: Pain with test 1: obvious deviations were noted 2: subtle deviations were noted 3: if no compensations or deviations were present. Deviations: • pelvis did not remain in neutral (rotation occurred in sagittal, frontal (i.e. hip hike), or transverse plane), • spine did not remain neutral (rotation occurred in sagittal, frontal or transverse plane), • lack of symmetry in test performance between the left and right side, and/or • any trunk movement prior to, during, or after active hip abduction. Total Possible Points: 6
Overhead squat[24] 	The subject grasps a piece of PVC pipe in both hands with arms approximately shoulder width apart. Standing with feet shoulder width apart, toes pointing forward and arms overhead, the subject squats as deeply as possible 3 times. The rater evaluates from the front, side, and back. If the subject was unable to complete the full motion in	0: pain with test 1: Unable to squat below parallel without compensations while using 2x6 board 2: Able to squat to below parallel with 2x6 board 3: Able to squat to below parallel without 2x6 board and no compensations. Total Possible Points: 3

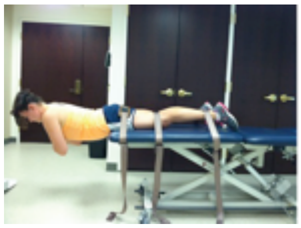
	an error-free fashion, a wooden 2x6 was placed under the subject's heels and the squat was re-evaluated.	
Modified Thomas test[62,63] 	Subject sits on the edge of the table and then lies back onto the table pulling both knees to the chest. Holding their left knee in this position, subjects then lower the right leg toward the table.	0: Pain with test 1: limitation on both sides 2: limitation on one side 3: No limitations Total Possible Points: 3
In-line lunge[24] 	Subject stands with toes on the starting line of 2x6 board. The lead leg heel is placed at a distance equal to the height of the tibial tuberosity. Subject grasps the PVC pipe along the spine so it touches the back of the head, upper back and the middle of the buttocks. Subjects' right/left hand should be against the back of your neck, and the left/right hand should be against your lower back.	0: Pain with test 1: obvious deviations were noted 2: subtle deviations were noted 3: if no compensations or deviations were present. Deviations: • Dowel does not remain in contact with trunk, • trunk and dowel do not remain vertically aligned, • feet do not remain in sagittal plane, • knee does not touch board behind heel of front foot, • subject loses balance and falls off the board Total Possible Points: 6
Hurdle step[24]	Subjects stood with their feet together and toes touching the board. Grasping the dowel with both hands, they placed the dowel behind their neck and across the shoulders. From this position, they were	0: Pain with test 1: if contact between the moving foot and hurdle occurred or if a loss of balance was observed 2: if alignment was lost between hips, knees and ankles or the dowel did not

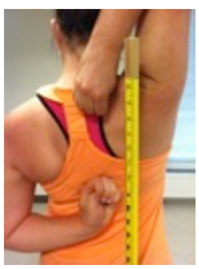
	instructed to maintain an upright posture, raise the right leg and step over the hurdle, making sure to raise the moving foot towards the shin. Once the hurdle was cleared, subjects touched the floor with their heel and returned to the starting position while maintaining alignment of the ankle, knee and hip.	remain horizontal 3: if the test was performed without any compensation or limitation. *The leg stepping over the hurdle was the leg being scored Total Possible Points: 6
Rotary stability[37]   	Subjects assumed a quadruped position with the hips and knees at 90° and a 2x6 board between their hands and knees. With the ankles dorsiflexed, toes, knees, and thumbs touching the board, the subject raised the arm and extended the ipsilateral hip and knee simultaneously. After achieving this position, subjects brought the elevated elbow and knee towards the midline of the body to make contact above the board and then return to the starting position.	0: pain with test 1: unable to perform the diagonal pattern 2: unable to perform the ipsilateral pattern but able to perform the diagonal 3: able to perform the ipsilateral pattern Total Possible Points: 6
Trunk stability push-up[37]  	Subjects lied face down with arms extended overhead and the hands shoulder width apart. The thumbs were then moved down in line with forehead for men, chin for women. Subjects positioned legs together, toes toward the shins and knees and elbows off the ground. While maintaining a rigid torso, subjects pushed their body as one unit into a pushup position. *If unable to perform move hands to chin*	0: Pain with test 1: Body does not lift as one unit, even with hand re-alignment. 2: Body lifts as one unit, but required hand re-alignment 3: Body lifts as one unit, no hand re-alignment. Total Possible Points: 3

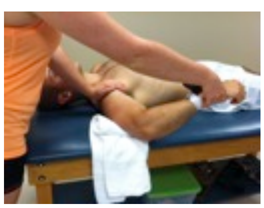
	level for MALE and clavicle level of FEMALE subjects.	
Trunk flexion/extension mobility[37]  	Subjects assumed a quadruped position and were instructed to rock their hips toward their heels, lower their chest to their knees, and reach their hands in front of their body as far as possible. The trunk extension mobility test began with subjects lying prone on an exercise mat with the hands directly under the shoulders and the feet together. From this position, subjects were instructed to press their chest off the mat as much as possible by straightening the elbows and without any lower body movement. Raters observed for limited or excessive motion in the shoulder (flexion test only), thoracic and lumbar spines, and hips.	0: pain was present during either test 1: if there was limited or excessive motion observed on both tests 2: if there was limited or excessive motion observed on only one test 3: if no excessive or limited motion was observed on either test Total Possible Points: 3
Step down[64] 	Subjects were instructed to stand on a 20-cm stool, cross their arms across their chest, and squat down as far as possible (attempting to touch the reaching heel to the ground) five times consecutively. Subjects were also instructed to perform the movement in a slow and controlled manner while maintaining their balance. If a subject was unable to touch the reaching heel to the ground, they were instructed to stop at approximately 60° of knees flexion. Raters provided verbal feedback, if needed,	0: pain during test 1: obvious deviations were noted 2: subtle deviations were noted 3: if no compensations or deviations were present Deviations: pelvis did not remain neutral, trunk did not remain in a neutral vertically aligned position, knee collapsed toward midline of the body, stance heel lifted from the step, loss of balance, and inability to achieve at least 60° knee flexion.

	to subjects who were unable to reach the heel to the ground. This was done to ensure that any compensations or deviations observed were not a function of step height.	Total Possible Points: 6
Single leg hop[65,66] 	Subjects performed one practice trial for each limb, followed by 2 measured and recorded trials. No restrictions were placed on arm movement during testing. To be deemed successful, the landing must have been maintained for 2 seconds. Once subjects successfully completed the hop, the recorded distance was marked at the location of heel of the leg being tested. Subjects were instructed to stand on one leg with their big toe behind the start line, jump forward as far as possible, land on the same foot that they jumped off of, and hold the landing for at least 2 seconds. The average of two trials was normalized to height.	EFA: Average hop distance on each leg normalized to height. Composite Scoring: 0: pain present during test 1: > 2 SD from normative mean 2: <2 and >1 SD from normative mean 3: <1 SD from normative mean Total Possible Points: 6
Y-Balance Test Anterior[55,66] 	The Y-Balance test set up in the current study utilized a wooden platform (get dimensions) with a PVC encasement that included an anterior reach PVC pipe centrally located in front of the subject. Subjects were instructed to stand with their stance foot in the middle of the platform so that their toes were behind the start line, hands on hips, and reach forward pushing	EFA: Average reach distance on each leg normalized to height. Composite Scoring: 0: pain present during test 1: > 2 SD from normative mean 2: <2 and >1 SD from normative mean 3: <1 SD from normative mean Total Possible Points: 6

	the indicator box as far as possible in one smooth movement. After the subject pushed the box as far as possible, the distance was recorded, subjects returned to single leg stance, the box was returned to the starting position, and two more trials were performed. Trials were deemed unsuccessful if at any point the hands came off the hips, the stance heel was lifted, or a loss of balance was observed. The average of three trials was normalized to height.	
Active straight leg raise[37] 	This test was performed with the subject lying supine on a mat table with a 2x6 board directly under the knees, toes pulled towards the shin, and the arms by the side. From this position, subjects were instructed to raise their left leg as high as possible, while keeping the left leg straight and the right knee against the board.	0: pain with test 1: if the vertical line of the malleolus of the moving leg is below the knee joint line of the non-moving leg 2: if the vertical line of the malleolus of the moving leg is between the mid-thigh and knee joint line of the non-moving leg 3: if the vertical line of the malleolus of the moving leg is above the mid-thigh of the non-moving leg Total Possible Points: 6
Double-leg lowering test[67] 	Subjects were instructed to lie on their back with their legs straight and their hips flexed to 90°. From this position, they were instructed to slowly lower their legs towards the floor without changing the pressure in the blood pressure cuff under their lumbar spine. Once the pressure changes 10 mm	EFA: Angle (degrees) in which they were able to lower their legs before changing pressure in the cuff. Composite Scoring: 0: pain present during test 1: > 2 SD from normative mean 2: <2 and >1 SD from normative mean

	Hg, the angle of the legs relative to the horizontal is recorded.	3: <1 SD from normative mean Total Possible Points: 3
Trunk extensor endurance[68] 	Subjects lied on their stomach, with ASIS of pelvis at the edge of the table and torso hanging off table. 3 mobilization belts across the buttocks, posterior thigh above the knee, and at the ankles were used to secure the subject to the table. Keeping the arms across the chest, subjects lifted the chest so that the torso was parallel to the floor. The test was terminated when the subject was no longer able to maintain their trunk in the test position as indicated by a 10° change in trunk alignment.	EFA: Total time in position (s). Composite Scoring: 0: pain present during test 1: > 2 SD from normative mean 2: <2 and >1 SD from normative mean 3: <1 SD from normative mean Total Possible Points: 3
Trunk flexor endurance[68] 	Subjects sat in a hooklying position (similar to the up position of a sit-up) with a 60° wedge touching their back. Raters then removed the wedge back 10°. Keeping the hands across the chest they were asked maintain this position for as long as possible. The test was terminated when the subject was no longer able to maintain their trunk in the test position as indicated by a 10° change in trunk alignment.	EFA: Total time in position (s). Composite Scoring: 0: pain present during test 1: > 2 SD from normative mean 2: <2 and >1 SD from normative mean 3: <1 SD from normative mean Total Possible Points: 3
Scapular dyskinesis[69]	The test consists of 5 repetitions of bilateral, active shoulder flexion and shoulder abduction (frontal plane). Each motion was demonstrated, and subjects	0: pain was present during the movement 1: if there was obvious winging or dysrhythmia observed on 3/5 trials in either flexion or abduction

	were allowed to perform a few practice trials. Perform the movements with a 2lb (< 150 lbs) or 4lb (> 150 lbs) weight in each in hand. Subjects began standing in a neutral position, arms at the side of the body, elbows straight, and thumbs pointing up. Raters stood 2-3m behind the subject to observe scapular motion.	2: if there was subtle winging or dysrhythmia observed on 3/5 trials in either flexion or abduction 3: if no winging or dysrhythmia was observed. Total Possible Points: 6
Shoulder mobility[37]  	Subjects were instructed to stand tall with their feet together and arms hanging comfortably. Then, they made a fist so their fingers were around the thumbs and in one motion, placed the right fist overhead and down their back as far as possible while simultaneously taking their left fist up their back as far as possible. They were instructed not to "creep" their hands closer after their initial placement. Raters measured the distance between the two closest bony prominences on the subjects' hands using a standard cloth tape measure (measured to the nearest 0.5 in). Raters measured the subjects' hand length prior to testing. Hand length was measured from the most distal wrist crease to the tip of the third digit. Raters recorded the distance of the closest reach. If the subject was able to touch their hands together, then a distance of zero was recorded for that side.	EFA: Distance (inches) between two closest bony prominences. Composite Scoring: 0: pain present during test 1: >1.5 hand lengths apart 2: > 1 hand length apart 3: < 1 hand length apart Total Possible Points: 6

Closed kinetic chain upper extremity stability[56,70]  	Two lines of tape were placed 36 inches apart on the floor. Subjects started the test in a standard push-up position, with one hand on each tapeline. Subjects were allowed a practice trial to ensure proper form, defined as: feet shoulder width apart; shoulders, hips, knees and ankles aligned in the coronal plane; and each hand must touch the opposite line to count as a repetition. To perform the test, subjects brought one hand over to the opposite tape line, returned to the starting tapeline, and then repeated the task with the opposite hand.	EFA: Average number of touches in 15 seconds. Composite Scoring: 0: pain present during test 1: > 2 SD from normative mean 2: <2 and >1 SD from normative mean 3: <1 SD from normative mean Total Possible Points: 3
Glenohumeral internal rotation deficit[71]  	The GIRD measurement included passive range of motion measurements of shoulder internal and external rotation with the subject supine, the arm in 90 degrees of abduction, elbow flexed to 90 degrees, and the forearm in a neutral position (palm facing the subject's feet). A digital inclinometer was placed along the dorsal aspect of the midline of the subject's forearm. The end of the inclinometer nearest the wrist was aligned with the distal most aspect of the ulnar head. The start position (zero degrees) for both internal and external rotation measures was as follows: shoulder in 90° of abduction, elbow flexed to 90°, forearm in neutral with	EFA: Nondominant (ND) and dominant (D) internal rotation percent contribution to total arc motion. Composite Scoring: 0: pain present during test 1: if GIRD (non-dominant minus dominant IR difference >14 AND non-dominant minus dominant total arc difference > 10 2: > 10 degree difference in total arc motion between sides, but IR difference < 14 3: <10 degree difference in total arc motion between sides Total Possible Points: 3

	the subject's hand/fingers pointing up towards the ceiling. From this position, the tester moved the glenohumeral joint into external or internal rotation.	
Unilateral hip bridge endurance[47] 	The unilateral hip bridge was performed with the subject lying supine with their arms across their chest, knees in 90° of flexion, and feet flat on the table (Figure 3c). The subject performed a double-leg hip bridge, and once a neutral spine and pelvis position were achieved the subject was instructed to extend one knee (randomly determined) so their leg was straight and their thighs were parallel to one another. Subjects were instructed to hold this position as long as possible. The test was terminated when they were no longer able to maintain a neutral pelvic position as noted by 10° change in transverse or sagittal plane alignment. Pelvic positioning in the transverse plane was monitored by a digital inclinometer attached to a mobilization belt that was tightly secured to the individual's pelvis. A second rater visually assessed sagittal plane alignment. Two trials were performed on each side and the average of each side was used for subsequent analyses.	EFA: Average time of two trials on each side (s). Composite Scoring: 0: pain present during test 1: > 2 SD from mean 2: <2 and >1 SD from mean 3: <1 SD from mean Total Possible Points: 6
Clinical Core Stability Test	This test was performed by	EFA: Average time of two

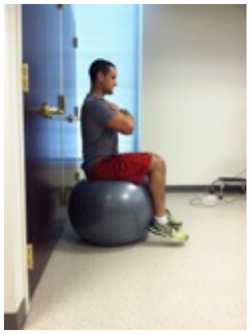
(CCCT) 	having subjects sit on either a 65 or 75cm Swiss ball with both feet off the ground for as long as possible. The size of the ball allowed both ankles to be in a neutral position (0° dorsiflexion) with the knees and hips in 90° +/- 10° of flexion when the feet were on the floor. Subjects sat up tall with their arms across their chest and lift their feet from the floor while maintaining heel contact with the ball. The ball was placed 6-8 inches from the wall. A 30-second practice trial was performed where subjects were given verbal feedback, the feet were allowed to touch the ground as needed, and the ball was allowed to touch the wall behind them. Two test trials were performed where the subject repeated the same procedures as the practice trial, however the test was terminated once the ball touched the wall or the feet touched the ground. Total time from when the feet were lifted from the ground to when the test was terminated was recorded.	trials. Composite Scoring: 0: pain present during test 1: > 2 SD from mean 2: <2 and >1 SD from mean 3: <1 SD from mean Total Possible Points: 3

Table 2. Athlete Characteristics by Sex (mean ± standard deviation)

	N	Age (years)	Height (cm)	Weight (kg)	Baecke Score
Female	25	21.8 ± 3.9	168.2 ± 8.6	68.1 ± 12.4	5.2 ± 0.6
Male	55	20.9 ± 3.0	179.8 ± 7.7	92.0 ± 17.4	6.6 ± 1.0

Table 3. Breakdown of Athletes by Sport

Sport	N	Sport	N
Football	27	**Tennis**	4
Baseball/Softball	10	**Track & Field**	4
CrossFit/Weightlifting	10	**Basketball**	2
Swimming/Water Polo	9	**Lacrosse**	2
Crew/Sailing	5	**Soccer**	1
Wrestling/Rugby	5	**Rock Climbing**	1

Table 4. Factor Analysis Non-rotated Factor Matrix

Test Items	Factor						
	LE MPE	UE/LE MOB	DYN STAB	TP STAB	TP STAB UE/LE motion	DYN MPE	TP MOB
SB AHA-R	0.529						
Squat					0.439		
Hurdle-L	0.636						
Hurdle-R	0.533						
RS- L					0.400		
RS-R					0.465		
DLLT	-0.549						
Step-L	0.536						
Step-R	0.666						
Hop-L			0.769				
Hop-R			0.718				
YBT-L						0.521	
YBT-R						0.461	
ShoMob-L		-0.594					
ShoMob-R		-0.772					
UHBE-L				0.653			
UHBE-R				0.640			
CKCUEST			0.529				
Scap Dys-R							
ASLR-L		0.636					
ASLR-R		0.616					
Flex/Ext Mob							0.495
ND IR cont		0.516					
D IR cont		0.515					
% Variance Explained	15.0 %	12.1 %	10.3 %	8.2 %	6.3 %	6.2 %	4.8 %
Total Variance Explained	62.9 %						

Abbreviations: MPE: movement pattern efficiency; MOB: mobility; STAB: stability; UE: upper extremity; LE: lower extremity; TP: trunk/pelvis; DYN: dynamic; SBAHA-R: side bridge with active hip abduction right; Squat: overhead squat; Hurdle: Hurdle step left/right; RS-L: rotary stability left; RS-R: rotary stability right; DLLT: double leg lowering test; Step-L: step down left; Step-R: step down right; Hop-L: single leg hop left; Hop-R: single leg hop right; YBT-L: Y-Balance Test left; YBT-R: Y-Balance Test right; ShoMob-L: shoulder mobility left; ShoMob-R: shoulder mobility right; UHBE-L: unilateral hip bridge endurance left; UHBE-R: unilateral hip bridge endurance right; CKCUEST: closed kinetic chain upper extremity stability test; Scap Dys-R: scapular dyskinesis right; ASLR-L: active straight leg raise left; ASLR-R: active straight leg raise right; Flex/Ext Mob: trunk flexion and extension mobility; ND IR cont: non-dominant internal rotation contribution; D IR cont: dominant internal rotation contribution

Table 5. MSST Individual Test Inter-Rater Reliability.

	Kappa (p-value)		
Test*	**Fault/No Fault**	**Amount of Deviation**	**Known/published reliability**
SB AHA-R	0.31 (0.01)	0.26 (0.01)	NA
Squat	0.81 (0.00)	0.78 (0.00)	k = 1.00[38]
Hurdle-L	0.94 (0.00)	0.81 (0.00)	k = 0.33[38]
Hurdle-R	0.94 (0.00)	0.79 (0.00)	k = 0.33[38]
RS- L	No covariance	No covariance	No covariance[38]
RS-R	No covariance	No covariance	No covariance[38]
Step-L	0.91 (0.00)	0.73 (0.00)	ICC = 0.94[72]; k=0.6-0.8[64]
Step-R	0.73 (0.00)	0.68 (0.00)	ICC = 0.94[72]; k=0.6-0.8[64]
ASLR-L	0.97 (0.00)	No covariance	k = 0.88[38]
ASLR-R	0.97 (0.00)	No covariance	k = 0.88[38]
Flex/Ext Mob	0.94 (0.00)	0.81 (0.00)	NA
GIRD	NA	NA	ICC = 0.54-0.57[58]
Hop-L	NA	NA	NA
Hop-R	NA	NA	NA
YBT-L	NA	NA	ICC = 0.99-1.00[55]
YBT-R	NA	NA	ICC = 0.99-1.00[55]
ShoMob-L	NA	NA	k = 0.90[38]
ShoMob-R	NA	NA	k = 0.90[38]
UHBE-L	NA	NA	NA
UHBE-R	NA	NA	NA
CKCUEST	NA	NA	NA
Scap Dys-R	NA	NA	k = 0.48-0.61[57]
DLLT	NA	NA	ICC = 0.63[67]

*Only tests that loaded on a factor are presented.

Abbreviations: Abbreviations: SBAHA-R: side bridge with active hip abduction right; Squat: overhead squat; Hurdle: Hurdle step left/right; RS-L: rotary stability left; RS-R: rotary stability right; DLLT: double leg lowering test; Step-L: step down left; Step-R: step down right; Hop-L: single leg hop left; Hop-R: single leg hop right; YBT-L: Y-Balance Test left; YBT-R: Y-Balance Test right; ShoMob-L: shoulder mobility left; ShoMob-R: shoulder mobility right; UHBE-L: unilateral hip bridge endurance left; UHBE-R: unilateral hip bridge endurance right; CKCUEST: closed kinetic chain upper extremity stability test; Scap Dys-R: scapular dyskinesis right; ASLR-L: active straight leg raise left; ASLR-R: active straight leg raise right; Flex/Ext Mob: trunk flexion and extension mobility; ND IR cont: non-dominant internal rotation contribution; D IR cont: dominant internal rotation contribution; NA: not assessed due to time constraints.

REFERENCES

1. National Center for Injury Prevention and Control. CDC Injury Research Agenda. US Department of Health and Human Services; 2002.

2. Griffin LY, Albohm MJ, Arendt EA, et al. Understanding and preventing noncontact anterior cruciate ligament injuries: a review of the Hunt Valley II meeting, January 2005. *Am J Sports Med.* Sep 2006;34(9):1512-1532.

3. Laudner K, Sipes, R. The Incidence of Shoulder Injury among Collegiate Overhead Athletes. *J Intercollegiate Sport.* 2009;2:260-268.

4. McFarland EG, Wasik M. Epidemiology of collegiate baseball injuries. *Clin J Sport Med.* Jan 1998;8(1):10-13.

5. Hewett TE, Myer GD, Ford KR. Reducing knee and anterior cruciate ligament injuries among female athletes: a systematic review of neuromuscular training interventions. *J Knee Surg.* Jan 2005;18(1):82-88.

6. Songer TJ, LaPorte RE. Disabilities due to injury in the military. *Am J Prev Med.* Apr 2000;18(3 Suppl):33-40.

7. Lincoln AE, Smith GS, Amoroso PJ, et al. The natural history and risk factors of musculoskeletal conditions resulting in disability among US Army personnel. *Work.* 2002;18(2):99-113.

8. Jones BH, Knapik JJ. Physical training and exercise-related injuries. Surveillance, research and injury prevention in military populations. *Sports Med.* Feb 1999;27(2):111-125.

9. Knapik JJ, Bullock SH, Canada S, et al. Influence of an injury reduction program on injury and fitness outcomes among soldiers. *Inj Prev.* Feb 2004;10(1):37-42.

10. Knapik JJ, Canham-Chervak M, Hauret K, et al. Discharges during U.S. Army basic training: injury rates and risk factors. *Mil Med.* Jul 2001;166(7):641-647.

11. Knapik JJ, Jones SB, Darakjy S, et al. Injury rates and injury risk factors among U.S. Army wheel vehicle mechanics. *Mil Med.* Sep 2007;172(9):988-996.

12. Gregg S. Musculoskeletal Conditions per M2 Database Analysis for FY 2007. Ft. Sam Houston2008.

13. Activity AMS. U. S. Army for Health Promotion and Preventative Medicine. 2005; http://afhsc.army.mil/home.

14. Mandelbaum BR, Silvers HJ, Watanabe DS, et al. Effectiveness of a neuromuscular and proprioceptive training program in preventing anterior cruciate ligament injuries in female athletes: 2-year follow-up. *Am J Sports Med.* Jul 2005;33(7):1003-1010.

15. Hewett TE, Torg JS, Boden BP. Video analysis of trunk and knee motion during non-contact anterior cruciate ligament injury in female athletes: lateral trunk and knee abduction motion are combined components of the injury mechanism. *Br J Sports Med.* Jun 2009;43(6):417-422.

16. Zazulak BT, Hewett TE, Reeves NP, et al. Deficits in neuromuscular control of the trunk predict knee injury risk: a prospective biomechanical-epidemiologic study. *Am J Sports Med.* Jul 2007;35(7):1123-1130.

17. Zazulak BT, Hewett TE, Reeves NP, et al. The effects of core proprioception on knee injury: a prospective biomechanical-epidemiological study. *Am J Sports Med.* Mar 2007;35(3):368-373.

18. Hewett TE, Myer GD, Ford KR, et al. Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: a prospective study. *Am J Sports Med.* Apr 2005;33(4):492-501.

19. Hagglund M, Walden M, Ekstrand J. Previous injury as a risk factor for injury in elite football: a prospective study over two consecutive seasons. *Br J Sports Med.* Sep 2006;40(9):767-772.

20. Messina DF, Farney WC, DeLee JC. The incidence of injury in Texas high school basketball. A prospective study among male and female athletes. *Am J Sports Med.* May-Jun 1999;27(3):294-299.

21. Boden BP, Griffin LY, Garrett WE, Jr. Etiology and Prevention of Noncontact ACL Injury. *Phys Sportsmed.* Apr 2000;28(4):53-60.

22. Griffin LY, Agel J, Albohm MJ, et al. Noncontact anterior cruciate ligament injuries: risk factors and prevention strategies. *J Am Acad Orthop Surg.* May-Jun 2000;8(3):141-150.

23. Croisier JL, Ganteaume S, Binet J, et al. Strength imbalances and prevention of hamstring injury in professional soccer players: a prospective study. *Am J Sports Med.* Aug 2008;36(8):1469-1475.

24. Cook G, Burton L, Hoogenboom B. Pre-participation screening: the use of fundamental movements as an assessment of function - part 1. *N Am J Sports Phys Ther.* May 2006;1(2):62-72.

25. Chorba RS, Chorba DJ, Bouillon LE, et al. Use of a functional movement screening tool to determine injury risk in female collegiate athletes. *N Am J Sports Phys Ther.* Jun 2010;5(2):47-54.

26. Cholewicki J, Silfies SP, Shah RA, et al. Delayed trunk muscle reflex responses increase the risk of low back injuries. *Spine (Phila Pa 1976).* Dec 1 2005;30(23):2614-2620.

27. Ireland ML, Willson JD, Ballantyne BT, et al. Hip strength in females with and without patellofemoral pain. *J Orthop Sports Phys Ther.* Nov 2003;33(11):671-676.

28. Tate A, Turner GN, Knab SE, et al. Risk factors associated with shoulder pain and disability across the lifespan of competitive swimmers. *J Athl Train.* Mar-Apr 2012;47(2):149-158.

29. Garrison JC, Arnold A, Macko MJ, et al. Baseball players diagnosed with ulnar collateral ligament tears demonstrate decreased balance compared to healthy controls. *J Orthop Sports Phys Ther.* Oct 2013;43(10):752-758.

30. Silfies SP, Ebaugh D, Pontillo M, et al. Critical Review of the Impact of "Core Stability" on Upper Extremity Athletic Injury and Performance. *Braz J Phys Ther.* 2015; 19(5): 360-368.

31. Kibler WB, Press J, Sciascia A. The role of core stability in athletic function. *Sports Med.* 2006;36(3):189-198.

32. Kibler WB, McMullen J. Scapular dyskinesis and its relation to shoulder pain. *J Am Acad Orthop Surg.* Mar-Apr 2003;11(2):142-151.

33. Martin C, Bideau B, Bideau N, et al. Energy flow analysis during the tennis serve: comparison between injured and noninjured tennis players. *Am J Sports Med.* Nov 2014;42(11):2751-2760.

34. Cook G, Burton L, Hoogenboom BJ, et al. Functional movement screening: the use of fundamental movements as an assessment of function - part 1. *Int J Sports Phys Ther.* May 2014;9(3):396-409.

35. McKeown I, Taylor-McKeown K, Woods C, et al. Athletic ability assessment: a movement assessment protocol for athletes. *Int J Sports Phys Ther.* Dec 2014;9(7):862-873.

36. Tarara DT, Hegedus EJ, Taylor JB. Real-time test-retest and interrater reliability of select physical performance measures in physically active college-aged students. *Int J Sports Phys Ther.* Dec 2014;9(7):874-887.

37. Cook G, Burton L, Hoogenboom B. Pre-participation screening: the use of fundamental movements as an assessment of function - part 2. *N Am J Sports Phys Ther.* Aug 2006;1(3):132-139.

38. Onate JA, Dewey T, Kollock RO, et al. Real-time intersession and interrater reliability of the functional movement screen. *J Strength Cond Res.* Feb 2012;26(2):408-415.

39. Shultz R, Anderson SC, Matheson GO, et al. Test-retest and interrater reliability of the functional movement screen. *J Athl Train.* May-Jun 2013;48(3):331-336.

40. Minick KI, Kiesel KB, Burton L, et al. Interrater reliability of the functional movement screen. *J Strength Cond Res.* Feb 2010;24(2):479-486.

41. Kiesel K, Plisky PJ, Voight ML. Can Serious Injury in Professional Football be Predicted by a Preseason Functional Movement Screen? *N Am J Sports Phys Ther.* Aug 2007;2(3):147-158.

42. Knapik JJ, Cosio-Lima LM, Reynolds KL, et al. Efficacy of functional movement screening for predicting injuries in coast guard cadets. *J Strength Cond Res.* May 2015;29(5):1157-1162.

43. Butler RJ, Contreras M, Burton LC, et al. Modifiable risk factors predict injuries in firefighters during training academies. *Work.* Jan 1 2013;46(1):11-17.

44. Burton SL. *Performance and injury predictability during firefighter candidate training (PhD Dissertation)*. Blacksburg, VA, Virginia Tech; 2006.

45. Hoover D, Killian CB, Bourcier B, et al. Predictive validity of the Functional Movement Screen in a population of recreational runners training for a half marathon. 55th Annual Meeting of the American College of Sports Medicine; 2008; Indianapolis, Indiana.

46. Cook G, Burton L, Hoogenboom BJ, et al. Functional movement screening: the use of fundamental movements as an assessment of function-part 2. *Int J Sports Phys Ther.* Aug 2014;9(4):549-563.

47. Butowicz CM, Ebaugh DD, Noehren B, et al. Validation of Two Clinical Measures of Core Stability. *Int J Sports Phys Ther.* Feb 2016;11(1):15-23.

48. Hegedus E, McDonough S, Bleakley C, et al. Physical performance tests predict injury in National Collegiate Athletic Association athletes: a three-season prospective cohort study. *Br J Sports Med.* 2016.

49. Field A. *Discovering Statistics Using SPSS.* Third Edition ed. London: Sage Publications, Ltd; 2009.

50. Leech NL, Barrett KC, Morgan GA. *SPSS for Intermediate Statistics.* New York: Lawrence Erlbaum Associates; 2008.

51. Landis JR, Koch GG. The measurement of observer agreement for categorical data. *Biometrics.* Mar 1977;33(1):159-174.

52. Portney LG, Watkins MP. *Foundations of Clinical Research: Applications to Research.* Third Edition ed. New Jersey: Pearson Education, Inc.; 2009.

53. Krause DA, Youdas JW, Hollman JH, et al. Abdominal muscle performance as measured by the double leg-lowering test. *Arch Phys Med Rehabil.* Jul 2005;86(7):1345-1348.

54. Munro AG, Herrington LC. Between-session reliability of four hop tests and the agility T-test. *J Strength Cond Res.* May 2011;25(5):1470-1477.

55. Plisky PJ, Gorman PP, Butler RJ, et al. The reliability of an instrumented device for measuring components of the star excursion balance test. *N Am J Sports Phys Ther.* May 2009;4(2):92-99.

56. Goldbeck T, Davies G. Test-retest reliability of the closed kinetic chain upper extremity stability test: a clinical field test. *Journal of Sports Rehabilitation.* 2000;9:35-45.

57. McClure P, Tate AR, Kareha S, et al. A clinical method for identifying scapular dyskinesis, part 1: reliability. *J Athl Train.* Mar-Apr 2009;44(2):160-164.

58. Kevern MA, Beecher M, Rao S. Reliability of measurement of glenohumeral internal rotation, external rotation, and total arc of motion in 3 test positions. *J Athl Train.* Sep-Oct 2014;49(5):640-646.

59. MacCallum R, Widaman K, Zhang S, et al. Sample size in factor analysis. *Psychol Methods.* 1999;4(1):84-89.

60. Lawley DN, Maxwell AE. *Factor analysis as a statistical method.* American Elsevier Pub. Co.; 1971.

61. Teyhen D, Bergeron MF, Deuster P, et al. Consortium for health and military performance and American College of Sports Medicine Summit: utility of functional movement assessment in identifying musculoskeletal injury risk. *Curr Sports Med Rep.* Jan-Feb 2014;13(1):52-63.

62. Peeler J, Anderson JE. Reliability of the Thomas test for assessing range of motion about the hip. *Physical Therapy in Sport.* 2007;8(1):14-21.

63. Harvey D. Assessment of the flexibility of elite athletes using the modified Thomas test. *Br J Sports Med.* Mar 1998;32(1):68-70.

64. Crossley KM, Zhang WJ, Schache AG, et al. Performance on the single-leg squat task indicates hip abductor muscle function. *Am J Sports Med.* Apr 2011;39(4):866-873.

65. Brumitt J, Heiderscheit BC, Manske RC, et al. Lower extremity functional tests and risk of injury in division iii collegiate athletes. *Int J Sports Phys Ther.* Jun 2013;8(3):216-227.

66. Pontillo M, Tomaszewski S, Sennett B. Reference values for the Y-Balance test and single-leg hop for distance in collegiate athletes. *J Orthop Sports Phys Ther.* 2014;44(1):A66.

67. Lanning CL, Uhl TL, Ingram CL, et al. Baseline values of trunk endurance and hip strength in collegiate athletes. *J Athl Train.* Oct-Dec 2006;41(4):427-434.

68. McGill SM, Childs A, Liebenson C. Endurance times for low back stabilization exercises: clinical targets for testing and training from a normal database. *Arch Phys Med Rehabil.* Aug 1999;80(8):941-944.

69. Kibler WB, Sciascia A. Current concepts: scapular dyskinesis. *Br J Sports Med.* Apr 2010;44(5):300-305.

70. Pontillo M, Spinelli B, Sennett B. Prediction of in-season shoulder injury from preseason testing in Division I collegiate football players. *Sports Health.* 2015;6(6):497-503.

71. Shanley E, Thigpen CA, Clark JC, et al. Changes in passive range of motion and development of glenohumeral internal rotation deficit (GIRD) in the professional pitching shoulder between spring training in two consecutive years. *J Shoulder Elbow Surg.* Nov 2012;21(11):1605-1612.

72. Loudon JK, Wiesner D, Goist-Foley HL, et al. Intrarater Reliability of Functional Performance Tests for Subjects With Patellofemoral Pain Syndrome. *J Athl Train.* Sep 2002;37(3):256-261.

CHAPTER FOUR: MOVEMENT SYSTEM PERFORMANCE DIFFERENCES IN ATHLETES WITH AND WITHOUT A NON-TRAUMATIC SHOULDER INJURY

COURTNEY M. BUTOWICZ, MSEd, CSCS[1]; D. DAVID EBAUGH, PhD, PT[1,2]; JIMMY ONATE, PhD, AT, ATC, FNATA[3]; STELLA VOLPE, PhD, RD, LDN, FACSM[4]; MARISSA PONTILLO, PT, DTP, SCS[1,5]; SHERI P.SILFIES. PhD, PT[1]

[1]Physical Therapy & Rehabilitation Sciences Department, Drexel University, Philadelphia, PA, USA

[2] Health Sciences Department, Drexel University, Philadelphia, PA, USA

[3]School of Health and Rehabilitation Sciences, The Ohio State University, Columbus, OH, USA

[4] Department of Nutrition Sciences, Drexel University, Philadelphia, PA, USA

[5]GSPP Penn Therapy and Fitness at Penn Sports Medicine Center, Philadelphia, PA, USA

Correspondence: Address all correspondence to Sheri P. Silfies, PT, PhD, Drexel University, Rehabilitation Sciences Spine Research Laboratory, Three Parkway, Mail Stop 7-502, Philadelphia, PA 19102-1192, USA. Tel: (267) 359-5580; Fax: (267) 359-5576.
Email: silfies@drexel.edu

Statement of Support: This work was supported in part by the American Physical Therapy Associations Sports Section Legacy Fund.

ABSTRACT

Background: Musculoskeletal injuries can have a detrimental effect on sports performance, psychosocial factors, and an increased risk of musculoskeletal impairments later in life. Athletic screening has gained popularity in efforts to identify poor performance and athletes potentially at increased risk of injury. Movement pattern efficiency, regional stability, mobility, and movement symmetry are proposed risk factors for upper and lower extremity athletic injury. Impairments in any of these risk factors may result in performance degradations and inefficient force generation and transfer through the kinetic chain. Current screening tests may not adequately assess core stability and upper extremity movement pattern efficiency and stability. Therefore, they may not adequately identify athletes at risk of upper extremity injury.

Purpose/Hypothesis: The primary purpose of this study was to determine the ability of a novel comprehensive movement system screen (MSST) to discriminate performance differences between athletes with and without non-traumatic shoulder injury. A secondary purpose was to determine if a subset of upper extremity tests within the MSST could discriminate performance differences between groups. The authors hypothesized that athletes with non-traumatic shoulder injury would demonstrate decreased MSST performance, and that the results may provide preliminary support for a subset of MSST tests that can identify athletes with a shoulder injury.

Study Design: Cross-Sectional design

Methods: Eighty-one collegiate and professional athletes (40 with injury, 41 without injury) completed the MSST.

Results: Athletes with non-traumatic shoulder injury (composite score = 56.5 ± 5.9) scored significantly lower than healthy controls (composite score = 59.5 ± 4.8) on the MSST ($t = 2.43$, $p = 0.02$, $d = 0.54$). Logistic regression revealed rotary stability, shoulder mobility dominant arm, and glenohumeral internal rotation deficit predicted whether or not an athlete had shoulder pain, $\chi^2 = 14.37$, $df = 5$, $N = 81$, $p = 0.01$.

Conclusions: The MSST was able to discriminate performance differences in athletes with and without non-traumatic shoulder injury. To date, this is the first comprehensive movement screen used to address non-traumatic upper extremity injury in athletes.

Levels of Evidence: Level III

Keywords: upper extremity athletic injuries, athletic screening, movement patterns, stability

INTRODUCTION

Participation in collegiate athletics has increased significantly in the past 25 years and subsequently so have the number of injuries. Approximately 12,500 athletic injuries are reported each year.[1] Sport-related injuries account for nearly $500 million in emergency room visit costs annually in the United States.[2] Non-traumatic shoulder injuries, such as rotator cuff tendinitis and shoulder impingement syndrome, will affect nearly 30% of all overhead athletes.[3] Upper extremity injuries account for nearly 75% of time lost to injury in collegiate baseball players, with 69% of these injuries reported in pitchers.[4] Injuries can have significant immediate and long-term effects on an athlete. These include, but are not limited to, degradations in athletic performance, loss of participation, repercussions regarding educational funding, depression, disability, and increased risk of life-long musculoskeletal impairments.[5]

Proposed risk factors such as impairments in movement pattern efficiency, regional stability (i.e. core stability), and symmetry of movement are commonly associated with non-contact sports injuries.[6-11] Pre-participation athletic screens are becoming more widely used in athletic settings to identify potential risk factors for musculoskeletal injury and assess performance. Currently, there are a limited number of pre-participation screens available to assess both upper extremity injury prevention/risk and athletic performance.[12]

Regional stability, specifically core stability, may have a direct link to movement pattern efficiency. Regional stability is defined as the ability to control the body region's position in order to withstand internal and external perturbations. Movement pattern efficiency is defined as the coordination of motion (timing and amount) between body segments and/or extremities to effectively accept, generate, or transfer forces to accomplish a skill or task. The kinetic chain model suggests that the core (comprised of the trunk, pelvis, and proximal extremity regions) is the mechanical link between the upper and lower extremities. This allows for the sequential coordination of body segments to effectively generate, transfer and dissipate forces within the movement system.[13] Many movements in sport, such as those seen in throwing and racquet sports, require energy to be transferred from the hips and trunk to the upper extremities. Coordinated muscular activity through the core is essential for this sequence of energy transfer from the proximal to distal segments. The inability to produce, transfer, and dissipate forces effectively can lead to increased loads on the upper extremity, increasing the potential for injury.[8,14]

The Functional Movement Screen (FMS), 16-item physical performance measure screening battery (16-PPM), and Athletic Ability Assessment (AAA) are pre-participation screens proposed to assess movement patterns and athletic performance capabilities. These screens use multi-segment movements in an attempt to identify breakdowns in the kinetic chain.[12,15-18] The FMS and AAA have reported very good to excellent composite score inter-rater reliability (ICC = 0.6-0.92 and 0.96, respectively).[12,18] The FMS and 16-PPM have reported test item inter-rater reliability of $k = 0.74\text{-}1.0$, ICC = 0.92-0.98 (FMS) and $k_w = 0.24\text{-}0.93$, ICC = 0.03-0.99 (16-PPM).[12,17] While no evidence currently exists to support the ability of the 16-PPM or AAA to predict injury, much work has been done to assess the predictive ability of the FMS. An FMS composite score (range 0-21) ≤ 14 has been reported to predict lower extremity injury in professional football players, collegiate athletes, military personnel, and first responders.[19-24] Recent work also suggests that athletes with performance asymmetry on any of the 5 tests within the FMS that are assessed bilaterally are 2.73 times more likely to sustain an injury than athletes without an asymmetry (relative risk = 2.73, 95% confidence interval=1.36-5.4, p =0.001).[25] However, there is conflicting evidence suggesting the FMS composite score may not be a valid predictor of injury.[25-31] A possible major limitation of the FMS is that it lacks an independent core stability assessment and shoulder movement pattern efficiency and/or stability assessment. The AAA and 16-PPM include independent core stability assessments, however, the 16-PPM is the only screen utilizing an upper extremity stability test. While these new screens attempt to address gaps within the FMS, the validity of these screens is unknown.

The Movement System Screening Tool (MSST) is a novel comprehensive screen designed to assess regional stability, movement pattern efficiency, mobility, and movement symmetry throughout the upper and lower extremities and the core. The MSST consists of 15 different tests represented by 6 tests for the lower extremity, 4 tests for the upper extremity, and 5 tests for the core (trunk/pelvis region). Each test was scored on a 0-3 scale with a maximum composite score 72 as 9 tests were performed bilaterally and received a score for each side.

The primary purpose of the current study was to determine the ability of the MSST to discriminate performance differences between athletes with and without non-traumatic shoulder injury. The authors hypothesized that athletes with non-traumatic shoulder injury would demonstrate decreased performance on the MSST. A secondary aim was to explore the potential for a subset of tests within the screen to also distinguish performance differences between groups.

METHODS

Study Design

This study used a known-groups design to assess the ability of the MSST to discriminate performance differences between athletes with and without non-traumatic shoulder injury. Using a known groups method allows for the choice of a criterion (i.e. MSST composite score) that can theoretically identify the presence or absence of a certain characteristic (i.e. shoulder pain).[32] Athletes completed the battery of clinical tests within the MSST screen. The 15 tests used in the MSST were compiled using a standardized iterative process that included: a comprehensive literature search, Delphi panel expert analysis, individual test inter-rater reliability, and an exploratory factor analysis (EFA). These 15 tests represent the *a priori* constructs (movement pattern efficiency, regional stability, and mobility) verified by region (upper extremity, lower extremity and core) using the EFA, which explained 63 % of variance (Butowicz dissertation Chapter 3-EFA/Reliability paper). Test items proposed to assess core stability were validated against lab-based biomechanical measures (Butowicz dissertation Chapter 2-core stability validity paper). Combined results of the EFA and core stability test validity suggest the tests included in the MSST demonstrate construct validity. Inter-rater reliability of the MSST composite score is ICC (2,1) = 0.94, 95% CI (0.91, 0.96). (Butowicz dissertation Chapter 3-EFA/Reliability paper).

Subjects

Eighty-one collegiate and professional athletes participated in the study with 40 of these athletes having a current shoulder injury. Sixty-five percent (26/40) of the athletes with a shoulder injury were currently receiving rehabilitation, but all had sought medical attention for shoulder pain within the last 6 months. Inclusion criteria were any athlete between the ages of 18-35, with a minimum participation of 10 hours per week in practice, games, and/or strength and conditioning workouts. An athlete was defined as any individual currently competing in any sport at a professional, semi-professional, varsity, junior varsity, or club level. Subjects were excluded if they presented with any of the following: concussion (current or within the last 6 months), current leg, trunk or neck injury, a diagnosed balance disorder, and/or a current head cold, sinus infection, or inner ear infection. Athletes with a shoulder injury were required to meet the following additional criteria: shoulder injury that was non-traumatic in nature, and onset of the injury or pain within the previous 6 months that had required the athlete to seek medical treatment. Athletes with shoulder injury were matched to athletes without shoulder injury by age within 5 years, gender, sport group [a) overhead athletes; b) athletes who use their upper extremities in their sports but are not overhead, e.g., lacrosse]; and body mass index (BMI) within 5 kg/m^2.

Procedures

Subjects attended one testing session and were asked to refrain from strenuous exercise 24 hours prior to testing to avoid potential effects of fatigue. Prior to the start of any testing procedures, participants signed informed consent documents approved by the (blinded) University Institutional Review Board. Height, weight, leg length, leg and arm dominance, hours of activity per week, sport, and current treatment status (shoulder injury group) were collected. Athletes completed the 15 tests within the MSST. Subjects performed up to three trials of each test. Each test was scored on a four-point scale (0-3). The scores on for each test were summed and the composite score used for analysis.

Tests

The tests within the MSST are intended to assess the core, upper and lower extremities. Within each of these body regions the tests are designed to assess movement pattern efficiency, stability, mobility, and symmetry of movement. A description of test procedures and scoring criteria are located in Table 1.

Upper Extremity Tests

The upper extremity tests are the shoulder mobility test (SHOMOM), glenohumeral internal rotation deficit (GIRD), closed kinetic chain upper extremity stability test (CKCUEST), and scapular dyskinesis test (SCAP). SHOMOB assesses bilateral active shoulder range of motion, assessing adduction with internal rotation of one shoulder and abduction with external rotation of the other.[33] SHOMOB has demonstrated almost perfect inter-rater agreement (k = 0.9) and inter-session reliability (k = 0.84).[12] GIRD assesses bilateral passive shoulder internal and external range of motion. Professional baseball pitchers with GIRD are nearly twice as likely to sustain a shoulder injury when compared to pitchers without GIRD.[34] GIRD was defined as an internal rotation difference greater than or equal to 15° between the dominant and non-dominant arms combined with a total arc of motion difference of greater than or equal to 10°. Passive shoulder range of motion is measured with the athlete supine, the shoulder abducted to 90°, and the elbow flexed to 90°. Passive internal and external range of motion measurements in this position (with tester overpressure) have reported fair to good inter-rater reliability (ICC 2,1 =0.54-0.57).[35]

The CKCUEST assesses dynamic stability of the shoulder complex in a closed chain activity. Collegiate football players who scored less than 21 touches during the test were 18 times more likely to sustain a shoulder injury than players who scored more than 21.[36] The CKCUEST has demonstrated excellent test-retest reliability in healthy college aged adults (ICC = 0.92).[37] Within the MSST, CKCUEST scores are based on reported normative means of 21.8 ± 3.9.[38] SCAP assesses scapulothoracic motion during 5 repetitions of bilateral, active shoulder flexion and shoulder abduction.[39] Inter-rater reliability of the scapular dyskinesis test has been reported as moderate to substantial in collegiate athletes (k_w = 0.48-0.61).[39]

Lower Extremity Tests

The lower extremity tests within the MSST include the active straight leg raise (ASLR), overhead squat (SQUAT), hurdle step (HURDLE), step down (STEP), single-leg hop (HOP), and Y-Balance Anterior (YBTA). ASLR assesses active hamstring and gastrocnemius range of motion while maintaining extension in the opposite limb.[33] ASLR has demonstrated almost perfect inter-rater reliability (k=0.88) and substantial test-retest reliability (k = 0.69).[12] The SQUAT assesses mobility of the thoracic spine, hips, knees, and ankles.[33] The SQUAT has demonstrated perfect inter-rater agreement (k = 1.00) and good inter-session reliability (k = 0.69).[12] HURDLE assesses coordination and stability of the trunk and pelvis during a stepping motion.[33] HURDLE has demonstrated slight test-retest reliability (k = 0.16) and fair inter-rater reliability (k = 0.31).[12]

The STEP is a clinical tool used to assess dynamic hip muscle function.[40] Inter-rater reliability of the STEP was reported as substantial (k=0.6) to excellent (k=0.8).[40] Poor performance on this test has been associated with hip abductor muscle dysfunction.[40] The HOP is a functional assessment of lower extremity strength, power, and neuromuscular control.[41] The HOP has reported good test-retest reliability ($ICC_{3,1}$ =

0.80).[42] Female collegiate athletes with a side-to-side asymmetry greater than 10% were 4 times more likely to sustain a foot or ankle injury (OR: 4.4, 95%CI: 1.2-15.4, $p = 0.02$) while their male counterparts who hopped more than 75% of their respective heights were at least 3 times more likely to sustain a low back or lower extremity injury (OR: 3.6, 95% CI: 1.2-11.2, $p = 0.03$).[43] Scoring was based on performance relative to established normative values.[44] The average of two trials was normalized to height.[44] Women's scores were based on means of 0.84 ± 0.17 (left) and 0.85 ± 0.17 (right). Men's scores were based on means of 1.04 ± 0.13 (left and right).

The Y-Balance Test assesses dynamic single limb postural control in three directions (anterior, posteromedial, and posterolateral). Athletes with an anterior reach (YBTA) difference between sides of greater than or equal to 4 cm have an increased risk of lower extremity injury (odds ratio: 2.3,95% confidence interval, 1.15–4.76).[45,46] The YBTA set up in the current study utilized a wooden platform with a PVC encasement that included an anterior reach PVC pipe centrally located in front of the subject. The Y-Balance test has reported good to excellent intra-rater and inter-rater reliability ($ICC_{3,1}$ = 0.85-0.91 and $ICC_{2,1}$ =0.99-1.00, respectively).[47] Scoring was based on performance relative to established normative values.[44] Women's scores were based on means of 0.427 ± 0.059 (left) and 0.428 ± 0.066 (right). Men's scores were based on means of 0.449 ± 0.064 (left) and 0.446 ± 0063 (right). The average of three trials was normalized to height.[44]

Core Tests

The tests focused on the core within the MSST include the trunk flexion/extension mobility (TRUNKMOB), side bridge with active hip abduction (SBAHA), rotary stability

(RS), double leg lowering test (DLLT), and unilateral hip bridge endurance (UHBE). TRUNKMOB is a combination of two mobility tests designed to assess trunk flexion and extension mobility. Inter-rater reliability determined on a subset of our subjects (n= 50) demonstrated substantial to almost perfect agreement between raters (k = 0.94, fault/no fault; k=0.81, amount of deviation). RS assesses trunk/pelvis stability during upper and lower extremity motion.[33] RS has demonstrated perfect inter-rater and test-retest agreement (k = 1.0).[12] SBAHA inter-rater reliability demonstrated fair to slight agreement between raters (k = 0.31, fault/no fault; k = 0.26, amount of deviation) on a subset of athletes in the study (n = 66).

The DLLT assesses an athlete's ability to control the position of the pelvis while lowering their legs from 90° of hip flexion. The DLTT has reported test-retest reliability ($ICC_{3,1}$= 0.98) [48] and ($ICC_{2,1}$=0.63).[49] Scoring was based on performance relative to established normative values.[49] Women's scores were based on means of 52.0° ± 5.0° while men's scores were based on means of 46.0° ± 3.0°. The UHBE is a recently validated assessment of multi-planar core neuromuscular control.[50] To date, no measurement property data have been reported. Scoring of this test was based on performance relative to normative values from within our lab. Scores were based off the following means and standard deviations: left = 19.56 ± 16.51s; right: 21.55 ± 21.12s.

Data Analysis

All statistical analyses were conducted using Statistical Package for the Social Sciences (version 22.0; SPSS Inc, Chicago, IL). Data missing at random were imputed using single imputation while non-random missing data were imputed using multiple imputations. The average of five imputations was used to derive data points for non-random missing data. The p-value for statistical significance was set at ≤ 0.05. An independent t-test was used to assess group differences in the MSST composite score in athletes with and without non-traumatic shoulder pain. A priori power analysis determined a sample size of 68 was needed (34 per group) to achieve significance at $p<0.05$ and power of 0.80 for a two-tailed independent t-test with an effect size of 0.8. Due to the lack of test-retest reliability and the preliminary nature of this screen, a large effect size [51] was chosen for this phase of the screen development. It was believed that if the screen could not separate athletes known to have a current injury from a matched healthy cohort with a large effect size, it would have difficulty predicting injury in a prospective study.

The CKCUEST was included as part of the MSST as per the Delphi expert panel analysis and results of an exploratory factor analysis. However, in an attempt to protect athletes with current shoulder injury from further potential injury, this test was not performed on this group. The statistical analysis was first performed with a CKCUEST score of zero being assigned to subjects with shoulder pain (max composite score of 75). However, it is impossible to know if all athletes with current shoulder pain would have received a zero score on this test. Therefore, to reduce potential bias of this approach, a second analysis was performed with the CKCUEST score removed from the composite score for all subjects.

To explore the development of a subset of MSST tests that could separate athletes with shoulder injury from athletes without shoulder injury, a logistic regression was performed. Variables selected for input into the logistic regression were determined by use of Mann-Whitney U tests with a p value of 0.1. Variables that were found to differ between groups were checked for multicollinearity. Variables that met the assumptions were entered into the regression model. Odds ratios and 95% confidence intervals for the odds ratios were calculated.

RESULTS

Less than 1% of the data were missing either at random or not at random. There were no significant differences in height, weight, or hours per week of sport activity between the groups. Descriptive statistics for all subjects are found in Table 2. A breakdown of athletes by sport is found in Table 3. Athletes with non-traumatic shoulder injury (composite score = 56.6 ± 5.8) scored significantly lower than healthy athletes (composite score = 62.2 ± 4.7) on the MSST with the CKCUEST included ($t = 4.74$, $p < 0.001$, $d = 1.05$). A large effect size was achieved with a mean difference between groups of 5.6 points. Analysis of the influence of the CKCUEST inclusion revealed no differences in the results of the t-test. The results of the t-test remained statistically significant when the CKCUEST was removed (shoulder pain group mean = 56.6 ± 5.8, control group mean = 59.5 ± 4.8, $t = 2.43$, $p = 0.02$, $d = 0.54$). The mean difference between groups was 2.9 points.

Logistic regression was conducted to assess whether the potential predictor tests of RS bilaterally, SHOMOB-dominant, and GIRD also significantly predicted whether or not an athlete had shoulder pain. These variables were chosen because they independently demonstrated significant ($p<0.1$) differences between groups. When considered together, these tests significantly predict whether or not an athlete had a shoulder injury 69% of the time, $\chi^2 = 14.37$, $df = 5$, $N = 81$, $p = 0.01$ (Table 4). Dominant arm shoulder mobility was the only variable with a significant odds ratio (OR: 0.38, $p = 0.05$, 95% CI: 0.15, 1.00).

DISCUSSION

The purpose of this study was to determine the ability of a novel comprehensive movement system screen (MSST) to discriminate between athletes with and without a current non-traumatic shoulder injury. There was a significant difference in composite MSST scores in athletes with and without non-traumatic shoulder pain. The calculated effect size ($d = 0.54$) represents a medium effect. This finding suggests that athletes with shoulder pain/injury demonstrate impairments within the movement system associated with the presence of pain.

Only 10% of athletes with a shoulder injury reported pain (received a score of zero) during performance of any upper extremity test. This low percentage suggests that pain with movement was not the primary factor driving the lower composite score in these athletes. However, because we utilized a known groups approach, it is unknown to what extent the pain group's current pain levels may have affected their overall performance. Since athletes in the pain group had a current shoulder injury, they may have developed compensatory movement strategies in order to avoid pain. The Penn Shoulder Score of the pain group (78.2) was significantly different [$t (78)= 10.0$, $p = 0.00$, $d = 2.2$] than the healthy control (97.5).

The MSST was designed as a comprehensive screen to assess regional stability, movement pattern efficiency, mobility, and movement symmetry in all body regions. The MSST attempts to address limitations of other published screens by including tests focused to core stability (e.g. unilateral hip bridge endurance and double-leg lowering test) and upper extremity movement pattern efficiency and/or stability tests (e.g. scapular dyskinesis and CKCUEST). Based on the kinetic chain model, performance degradations within any of these constructs may lead to breakdowns within the chain and potentially increase injury risk and/or hinder athletic performance. While each of these constructs is a proposed injury risk factor, their relationship to non-traumatic upper extremity injury is not fully understood. Evidence supports the relationship between impaired performance within these constructs and lower extremity and low back injury; yet, a paucity of evidence exists in relation to upper extremity injury.[11,20,25,45,52,53] The ability of the MSST to identify known groups with and without an upper extremity injury suggests some potential for use to predict shoulder injury pre-season. Future studies need to be conducted to determine the MSST's ability to predict upper extremity injuries in athletes. Additionally, future studies should determine the ability of the MSST to also predict lower extremity and low back athletic injuries.

A secondary aim of this study was to determine if a subset of MSST tests could correctly identify subjects in the known groups. Collectively the, rotary stability, GIRD, and dominant arm shoulder mobility tests were able to accurately predict group assignment in 69% of all cases. This subset of MSST tests has face validity as rotary stability is assessing core stability with upper extremity motion while GIRD is assessing internal rotation and shoulder mobility is assessing external rotation and abduction of the shoulder. These tests represent core stability and mobility, which are two proposed risk factors for upper extremity injury. The results of the logistic regression suggest that the odds of an athlete having shoulder pain are increased as dominant arm shoulder mobility performance decreases and when GIRD is present. Deficits in shoulder range of motion have been associated with shoulder injury in overhead athletes.[53,54] The findings of the current study support this association, as athletes with a current shoulder injury were more likely to have poorer scores on shoulder range of motion tests. Rotary stability, shoulder mobility, and GIRD could potentially be used as a subset of tests to predict upper extremity injuries in athletes. However, future studies should also include CKCUEST in the subset as previous work has demonstrated this test is associated with development of shoulder pain in football players.[36]

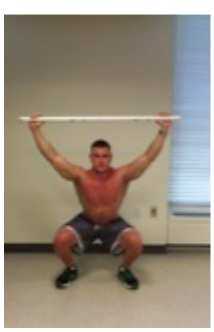
The current study assessed athletes with a current shoulder injury or an episode of shoulder pain within the previous 6 months, thus, it is unknown how well these athletes may have performed on the MSST before sustaining the injury. In an attempt to maintain the safety of the athletes with a current shoulder injury, the CKCUEST was not performed on this group. This created missing data points for this test. We could not confidently assume that every athlete with shoulder pain would have experienced pain with the test. Therefore the analysis of group differences was conducted with the CKCUEST included (shoulder pain subjects receiving a zero score for that test) and without the CKCUEST. Results demonstrated that MSST composite score was significantly different between groups in both cases ($p < 0.05$ without CKCUEST, $p < 0.001$ with CKCUEST). When the CKCUEST was included, there was a greater difference in composite scores between groups. This would be expected since all members of the injury group received a zero score while the control group received anywhere from 1-3 additional points. These results suggest that while MSST performance is different between groups without the CKCUEST, the potential to determine group differences may be increased when the CKCUEST is performed.

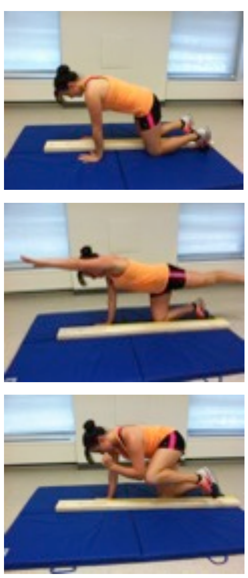
To date, the test-retest reliability of the MSST is unknown; therefore we cannot say that the group differences in the current study would exceed the minimal detectable change (MDC) of the screen. Future work should determine the 90% MDC of the screen. The design of the current study limits the ability to determine the screen's injury risk predictability. Future work should follow a prospective design to determine the screen's ability to accurately predict injury in an athletic population.

CONCLUSIONS

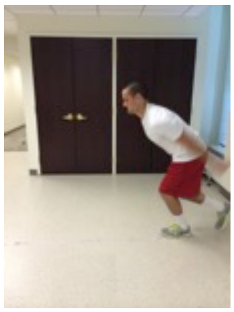
The results of this study suggest athletes with current or recent non-traumatic shoulder injury demonstrate performance degradations throughout the kinetic chain. These findings preliminarily support the use of the MSST as a screening tool to identify individuals with non-traumatic upper extremity injury. Future work is needed to determine the test-retest reliability and error measurement of the MSST. This study utilized a known groups design and as such future work should assess injury risk from a prospective design. By assessing proposed risk factors of injury within each body region, it may be possible for clinicians to identify athletes at risk of injury based on performance degradations in a region. This could potentially assist athletic trainers, physical therapists, or sports practitioners in identifying individuals that require further assessment or training interventions.

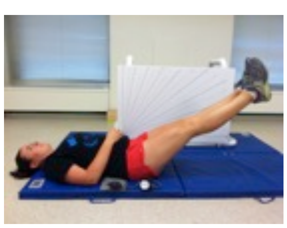
Table 1. Clinical tests within the Movement System Screening Tool (MSST).

Test	Description	Scoring
Side bridge with active hip abduction 	Subject lies on their side, propped up on the forearm with the shoulder over the elbow, and the bottom knee bent to 90 degrees. Top and bottom thighs should be inline with one another and the top leg should be straight and toes should be lifted towards the shin and pointed forward. Subject then lifts the pelvis off the floor/table until head, spine and bottom leg are in a straight line. Then they raise the top leg as high as possible.	0: Pain with test 1: obvious deviations were noted 2: subtle deviations were noted 3: if no compensations or deviations were present. Deviations: • pelvis did not remain in neutral (rotation occurred in sagittal, frontal (i.e. hip hike), or transverse plane), • spine did not remain neutral (rotation occurred in sagittal, frontal or transverse plane), • lack of symmetry in test performance between the left and right side, and/or • any trunk movement prior to, during, or after active hip abduction. Total Possible Points: 6
Overhead squat[16] 	The subject grasps a piece of PVC pipe in both hands with arms approximately shoulder width apart. Standing with feet shoulder width apart, toes pointing forward and arms overhead, the subject squats as deeply as possible 3 times. The rater evaluates from the front, side, and back. If the subject was unable to complete the full motion in an error-free fashion, a	0: pain with test 1: Unable to squat below parallel without compensations while using 2x6 board 2: Able to squat to below parallel with 2x6 board 3: Able to squat to below parallel without 2x6 board and no compensations. Total Possible Points: 3

	wooden 2x6 was placed under the subject's heels and the squat was re-evaluated.	
Hurdle step[16] 	Subjects stood with their feet together and toes touching the board. Grasping the dowel with both hands, they placed the dowel behind their neck and across the shoulders. From this position, they were instructed to maintain an upright posture, raise the right leg and step over the hurdle, making sure to raise the moving foot towards the shin. Once the hurdle was cleared, subjects touched the floor with their heel and returned to the starting position while maintaining alignment of the ankle, knee and hip.	0: Pain with test 1: if contact between the moving foot and hurdle occurred or if a loss of balance was observed 2: if alignment was lost between hips, knees and ankles or the dowel did not remain horizontal 3: if the test was performed without any compensation or limitation. *The leg stepping over the hurdle was the leg being scored Total Possible Points: 6
Rotary stability[15] 	Subjects assumed a quadruped position with the hips and knees at 90 degrees and a 2x6 board between their hands and knees. With the ankles dorsiflexed, toes, knees, and thumbs touching the board, the subject raised the arm and extended the ipsilateral hip and knee simultaneously. After achieving this position, subjects brought the elevated elbow and knee towards the midline of the body to make contact above the board and then return to the starting position.	0: pain with test 1: unable to perform the diagonal pattern 2: unable to perform the ipsilateral pattern but able to perform the diagonal 3: able to perform the ipsilateral pattern Total Possible Points: 6
Trunk flexion/extension mobility[15]	Subjects assumed a quadruped position and were instructed to rock their	0: pain was present during either test 1: if there was limited or

 	hips toward their heels, lower their chest to their knees, and reach their hands in front of their body as far as possible. The trunk extension mobility test began with subjects lying prone on an exercise mat with the hands directly under the shoulders and the feet together. From this position, subjects were instructed to press their chest off the mat as much as possible by straightening the elbows and without any lower body movement. Raters observed for limited or excessive motion in the shoulder (flexion test only), thoracic and lumbar spines, and hips.	excessive motion observed on both tests 2: if there was limited or excessive motion observed on only one test 3: if no excessive or limited motion was observed on either test Total Possible Points: 3
Step down[40] 	Subjects were instructed to stand on a 20-cm stool, cross their arms across their chest, and squat down as far as possible (attempting to touch the reaching heel to the ground) five times consecutively. Subjects were also instructed to perform the movement in a slow and controlled manner while maintaining their balance. If a subject was unable to touch the reaching heel to the ground, they were instructed to stop at approximately 60-degrees of knees flexion. Raters provided verbal feedback, if needed, to subjects who were unable to reach the heel to the ground. This was done to ensure that any compensations or deviations	0: pain during test 1: obvious deviations were noted 2: subtle deviations were noted 3: if no compensations or deviations were present Deviations: pelvis did not remain neutral, trunk did not remain in a neutral vertically aligned position, knee collapsed toward midline of the body, stance heel lifted from the step, loss of balance, and inability to achieve at least 60° knee flexion. Total Possible Points: 6

	observed were not a function of step height. This test was adapted from Crossley et al 2011.	
Single leg hop[43,44] 	Subjects performed one practice trial for each limb, followed by 2 measured and recorded trials. No restrictions were placed on arm movement during testing. To be deemed successful, the landing must have been maintained for 2 seconds. Once subjects successfully completed the hop, the recorded distance was marked at the location of heel of the leg being tested. Subjects were instructed to stand on one leg with their big toe behind the start line, jump forward as far as possible, land on the same foot that they jumped off of, and hold the landing for at least 2 seconds. The average of two trials was normalized to height. Test was adapted from Brumitt et al 2013 and Pontillo et al 2104.	Composite Scoring: 0: pain present during test 1: > 2 SD from normative mean 2: <2 and >1 SD from normative mean 3: <1 SD from normative mean Total Possible Points: 6
Y-Balance Test Anterior[44,47] 	The Y-Balance test set up in the current study utilized a wooden platform (get dimensions) with a pvc encasement that included an anterior reach pvc pipe centrally located in front of the subject. Subjects were instructed to stand with their stance foot in the middle of the platform so that their toes were behind the start line, hands on hips, and reach forward pushing the indicator box as far as	Composite Scoring: 0: pain present during test 1: > 2 SD from normative mean 2: <2 and >1 SD from normative mean 3: <1 SD from normative mean Total Possible Points: 6

	possible in one smooth movement. After the subject pushed the box as far as possible, the distance was recorded, subjects returned to single leg stance, the box was returned to the starting position, and two more trials were performed. Trials were deemed unsuccessful if at any point the hands came off the hips, the stance heel was lifted, or a loss of balance was observed. The average of three trials was normalized to height. This test was adapted from Plisky et al 2009 and Pontillo et al 2014.	
Active straight leg raise[15] 	This test was performed with the subject lying supine on a mat table with a 2x6 board directly under the knees, toes pulled towards the shin, and the arms by the side. From this position, subjects were instructed to raise their left leg as high as possible, while keeping the left leg straight and the right knee against the board.	0: pain with test 1: if the vertical line of the malleolus of the moving leg is below the knee joint line of the non-moving leg 2: if the vertical line of the malleolus of the moving leg is between the mid-thigh and knee joint line of the non-moving leg 3: if the vertical line of the malleolus of the moving leg is above the mid-thigh of the non-moving leg Total Possible Points: 6
Double-leg lowering test[49] 	Subjects were instructed to lie on their back with their legs straight and their hips flexed to 90 degrees. From this position, they were instructed to slowly lower their legs towards the floor without changing the pressure in the blood pressure cuff under their	Composite Scoring: 0: pain present during test 1: > 2 SD from normative mean 2: <2 and >1 SD from normative mean 3: <1 SD from normative mean Total Possible Points: 3

	lumbar spine. Once the pressure changes 10 mm Hg, the angle of the legs relative to the horizontal is recorded. This test was adapted from Lanning et al 2006.	
Scapular dyskinesis[55] 	The test consists of 5 repetitions of bilateral, active shoulder flexion and shoulder abduction (frontal plane). Each motion was demonstrated, and subjects were allowed to perform a few practice trials. Perform the movements with a 2lb (< 150 lbs) or 4lb (> 150 lbs) weight in each in hand. Subjects began standing in a neutral position, arms at the side of the body, elbows straight, and thumbs pointing up. Raters stood 2-3m behind the subject to observe scapular motion. This test was adapted from Kibler et al 2010.	0: pain was present during the movement 1: if there was obvious winging or dysrhythmia observed on 3/5 trials in either flexion or abduction 2: if there was subtle winging or dysrhythmia observed on 3/5 trials in either flexion or abduction 3: if no winging or dysrhythmia was observed. Total Possible Points: 6
Shoulder mobility[15]  	Subjects were instructed to stand tall with their feet together and arms hanging comfortably. Then, they made a fist so their fingers were around the thumbs and in one motion, placed the right fist overhead and down their back as far as possible while simultaneously taking their left fist up their back as far as possible. They were instructed not to “creep” their hands closer after their initial placement. Raters measured the distance between the two closest bony prominences on the	Composite Scoring: 0: pain present during test 1: >1.5 hand lengths apart 2: > 1 hand length apart 3: < 1 hand length apart Total Possible Points: 6

	subjects' hands using a standard cloth tape measure (measured to the nearest 0.5 in). Raters measured the subjects' hand length prior to testing. Hand length was measured from the most distal wrist crease to the tip of the third digit. Raters recorded the distance of the closest reach. If the subject was able to touch their hands together, then a distance of zero was recorded for that side.	
Closed kinetic chain upper extremity stability[56]  	Two lines of tape were placed 36 inches apart on the floor. Subjects started the test in a standard push-up position, with one hand on each tapeline. Subjects were allowed a practice trial to ensure proper form, defined as: feet shoulder width apart; shoulders, hips, knees and ankles aligned in the coronal plane; and each hand must touch the opposite line to count as a repetition. To perform the test, subjects brought one hand over to the opposite tape line, returned to the starting tapeline, and then repeated the task with the opposite hand.	Score: Average number of touches in 15 seconds. Composite Scoring: 0: pain present during test 1: > 2 SD from normative mean 2: <2 and >1 SD from normative mean 3: <1 SD from normative mean Total Possible Points: 3

Glenohumeral internal rotation deficit[53,57]  	The GIRD measurement included passive range of motion measurements of shoulder internal and external rotation with the subject supine, the arm in 90 degrees of abduction, elbow flexed to 90 degrees, and the forearm in a neutral position (palm facing the subject's feet). A digital inclinometer was placed along the dorsal aspect of the midline of the subject's forearm. The end of the inclinometer nearest the wrist was aligned with the distal most aspect of the ulnar head. The start position (zero degrees) for both internal and external rotation measures was as follows: shoulder in 90 degrees of abduction, elbow flexed to 90 degrees, forearm in neutral with the subject's hand/fingers pointing up towards the ceiling. From this position, the tester moved the glenohumeral joint into external or internal rotation.	Composite Scoring: 0: pain present during test 1: if GIRD (non-dominant minus dominant IR difference >14 AND non-dominant minus dominant total arc difference > 10 2: > 10 degree difference in total arc motion between sides, but IR difference < 14 3: <10 degree difference in total arc motion between sides Total Possible Points: 3
Unilateral hip bridge endurance[50] 	The unilateral hip bridge was performed with the subject lying supine with their arms across their chest, knees in 90 degrees of flexion, and feet flat on the table (Figure 3c). The subject performed a double-leg hip bridge, and once a neutral spine and pelvis position were achieved the subject was instructed to extend one knee (randomly determined) so their leg was	Score: Average time of two trials on each side (s). Composite Scoring: 0: pain present during test 1: > 2 SD from normative mean 2: <2 and >1 SD from normative mean 3: <1 SD from normative mean Total Possible Points: 6

	straight and their thighs were parallel to one another. Subjects were instructed to hold this position as long as possible. The test was terminated when they were no longer able to maintain a neutral pelvic position as noted by 10-degree change in transverse or sagittal plane alignment. Pelvic positioning in the transverse plane was monitored by a digital inclinometer attached to a mobilization belt that was tightly secured to the individual's pelvis. A second rater visually assessed sagittal plane alignment. Two trials were performed on each side and the average of each side was used for subsequent analyses.	

Table 2. Group descriptive statistics [mean (SD)]

Group	Sex (N women)	Age (yrs)	Height (cm)	Weight (kg)	Hours/week	Penn Shoulder Score
Healthy (n=40)	12	20.9 (3.4)	176.4 (9.5)	84.9 (18.5)	19.2 (5.6)	97.5 (3.9)
Injured (n=40)	13	21.4 (3.2)	176.2 (10.0)	84.6 (20.5)	18.7 (6.9)	78.2 (11.7)

Table 3. Breakdown of athletes by sport

Sport	N	Sport	N
Football	27	Tennis	4
Baseball/Softball	10	Track & Field	4
CrossFit/Weightlifting	10	Basketball	2
Swimming/Water Polo	9	Lacrosse	2
Crew/Sailing	5	Soccer	1
Wrestling/Rugby	5	Rock Climbing	1

Table 4. Logistic regression predicting athletes with a shoulder injury.

Variable	B	SE	Odds Ratio	p	95% CI	
					Lower	Upper
Rotary Stability-L	-.48	.54	.62	.37	.22	1.77
Rotary Stability-R	-.24	.42	.78	.62	.30	2.06
GIRD	-.65	.16	.52	.11	.24	1.16
Shoulder Mobility-Dominant Arm	-.96	.49	.38	.05	.15	1.00
Constant	5.72	1.95	303.59	.00		

REFERENCES

1. Dick R, Agel J, Marshall SW. National Collegiate Athletic Association Injury Surveillance System commentaries: introduction and methods. *J Athl Train.* Apr-Jun 2007;42(2):173-182.

2. Burt CW, Overpeck MD. Emergency visits for sports-related injuries. *Ann Emerg Med.* Mar 2001;37(3):301-308.

3. Laudner K, Sipes, R. The Incidence of Shoulder Injury among Collegiate Overhead Athletes. *J Intercollegiate Sport.* 2009;2:260-268.

4. McFarland EG, Wasik M. Epidemiology of collegiate baseball injuries. *Clin J Sport Med.* Jan 1998;8(1):10-13.

5. Hewett TE, Myer GD, Ford KR. Reducing knee and anterior cruciate ligament injuries among female athletes: a systematic review of neuromuscular training interventions. *J Knee Surg.* Jan 2005;18(1):82-88.

6. Leetun DT, Ireland ML, Willson JD, et al. Core stability measures as risk factors for lower extremity injury in athletes. *Med Sci Sports Exerc.* Jun 2004;36(6):926-934.

7. Liemohn WP, Baumgartner TA, Fordham SR, et al. Quantifying core stability: a technical report. *J Strength Cond Res.* 2010;24(2):575-579.

8. Kibler WB, Press J, Sciascia A. The role of core stability in athletic function. *Sports Med.* 2006;36(3):189-198.

9. Hewett TE, Myer GD, Ford KR, et al. Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: a prospective study. *Am J Sports Med.* Apr 2005;33(4):492-501.

10. Aguinaldo AL, Buttermore J, Chambers H. Effects of upper trunk rotation on shoulder joint torque among baseball pitchers of various levels. *J Appl Biomech.* Feb 2007;23(1):42-51.

11. Zazulak BT, Hewett TE, Reeves NP, et al. Deficits in neuromuscular control of the trunk predict knee injury risk: a prospective biomechanical-epidemiologic study. *Am J Sports Med.* Jul 2007;35(7):1123-1130.

12. Onate JA, Dewey T, Kollock RO, et al. Real-time intersession and interrater reliability of the functional movement screen. *J Strength Cond Res.* Feb 2012;26(2):408-415.

13. Kibler WB, McMullen J. Scapular dyskinesis and its relation to shoulder pain. *J Am Acad Orthop Surg.* Mar-Apr 2003;11(2):142-151.

14. Martin C, Bideau B, Bideau N, et al. Energy flow analysis during the tennis serve: comparison between injured and noninjured tennis players. *Am J Sports Med.* Nov 2014;42(11):2751-2760.

15. Cook G, Burton L, Hoogenboom B. Pre-participation screening: the use of fundamental movements as an assessment of function - part 2. *N Am J Sports Phys Ther.* Aug 2006;1(3):132-139.

16. Cook G, Burton L, Hoogenboom B. Pre-participation screening: the use of fundamental movements as an assessment of function - part 1. *N Am J Sports Phys Ther.* May 2006;1(2):62-72.

17. Tarara DT, Hegedus EJ, Taylor JB. Real-time test-retest and interrater reliability of select physical performance measures in physically active college-aged students. *Int J Sports Phys Ther.* Dec 2014;9(7):874-887.

18. McKeown I, Taylor-McKeown K, Woods C, et al. Athletic ability assessment: a movement assessment protocol for athletes. *Int J Sports Phys Ther.* Dec 2014;9(7):862-873.

19. Kiesel K, Plisky PJ, Voight ML. Can Serious Injury in Professional Football be Predicted by a Preseason Functional Movement Screen? *N Am J Sports Phys Ther.* Aug 2007;2(3):147-158.

20. Chorba RS, Chorba DJ, Bouillon LE, et al. Use of a functional movement screening tool to determine injury risk in female collegiate athletes. *N Am J Sports Phys Ther.* Jun 2010;5(2):47-54.

21. Knapik JJ, Cosio-Lima LM, Reynolds KL, et al. Efficacy of functional movement screening for predicting injuries in coast guard cadets. *J Strength Cond Res.* May 2015;29(5):1157-1162.

22. Butler RJ, Contreras M, Burton LC, et al. Modifiable risk factors predict injuries in firefighters during training academies. *Work.* Jan 1 2013;46(1):11-17.

23. Lisman P, O'Connor FG, Deuster PA, et al. Functional movement screen and aerobic fitness predict injuries in military training. *Med Sci Sports Exerc.* Apr 2013;45(4):636-643.

24. Garrison M, Westrick R, Johnson MR, et al. Association between the functional movement screen and injury development in college athletes. *Int J Sports Phys Ther.* Feb 2015;10(1):21-28.

25. Mokha M, Sprague PA, Gatens DR. Predicting Musculoskeletal Injury in National Collegiate Athletic Association Division II Athletes From Asymmetries and Individual-Test Versus Composite Functional Movement Screen Scores. *J Athl Train.* Jan 21 2016.

26. Burton SL. *Performance and injury predictability during firefighter candidate training (PhD Dissertation)*. Blacksburg, VA, Virginia Tech; 2006.

27. Hoover D, Killian CB, Bourcier B, et al. Predictive validity of the Functional Movement Screen in a population of recreational runners training for a half marathon. 55th Annual Meeting of the American College of Sports Medicine; 2008; Indianapolis, Indiana.

28. Morrell MD. *Lower extremity injury predictability of the Functional Movement Screen and the Star Excursion Balance Test (Master of Science Dissertation).* Toledo, OH, University of Toledo; 2012.

29. Munce TA, Dorman JC, Odney TO, et al. Using functional movement tests to assess injury risk and predict performance in Collegiate basketball players. American College of Sports Medicine Annual Meeting; 2012; San Francisco, CA.

30. Sorenson EA. *Functional movement screen as a predictor of injury in high school basketball athletes (Doctor of Philosophy Dissertation).* . Eugene, OR, University of Oregon; 2009.

31. Winke MR, Dalton K, Mendell J, et al. Prediction of in-season injuries using a preseason Functional Movement Screen in Collegiate athletes. American College of Sports Medicine Annual Meeting; 2012; San Francisco, CA.

32. Portney LG, Watkins MP. *Foundations of Clinical Research: Applications to Research.* Third Edition ed. New Jersey: Pearson Education, Inc.; 2009.

33. Cook G, Burton L, Hoogenboom BJ, et al. Functional movement screening: the use of fundamental movements as an assessment of function-part 2. *Int J Sports Phys Ther.* Aug 2014;9(4):549-563.

34. Wilk KE, Macrina LC, Fleisig GS, et al. Correlation of glenohumeral internal rotation deficit and total rotational motion to shoulder injuries in professional baseball pitchers. *Am J Sports Med.* Feb 2011;39(2):329-335.

35. Kevern MA, Beecher M, Rao S. Reliability of measurement of glenohumeral internal rotation, external rotation, and total arc of motion in 3 test positions. *J Athl Train.* Sep-Oct 2014;49(5):640-646.

36. Pontillo M, Spinelli B, Sennett B. Prediction of in-season shoulder injury from preseason testing in Division I collegiate football players. *Sports Health.* 2015;6(6):497-503.

37. Ellenbecker T, Manske R, Davies G. Closed kinetic chain testing techniques of the upper extremities. *Orthop Phys Ther Clin North Am.* 2000;9: 219-229.

38. Pontillo M, Huffman G, Sennett B. Profile of upper extremity rotator cuff strength and function in division I collegiate athletes. *J Orthop Sports Phys Ther.* 2011;41(1):A39-A51.

39. McClure P, Tate AR, Kareha S, et al. A clinical method for identifying scapular dyskinesis, part 1: reliability. *J Athl Train.* Mar-Apr 2009;44(2):160-164.

40. Crossley KM, Zhang WJ, Schache AG, et al. Performance on the single-leg squat task indicates hip abductor muscle function. *Am J Sports Med.* Apr 2011;39(4):866-873.

41. Reiman MP, Manske RC. *Functional Testing in Human Performance.* . Champaign, IL: Human Kinetics;; 2009.

42. Munro AG, Herrington LC. Between-session reliability of four hop tests and the agility T-test. *J Strength Cond Res.* May 2011;25(5):1470-1477.

43. Brumitt J, Heiderscheit BC, Manske RC, et al. Lower extremity functional tests and risk of injury in division iii collegiate athletes. *Int J Sports Phys Ther.* Jun 2013;8(3):216-227.

44. Pontillo M, Tomaszewski S, Sennett B. Reference values for the Y-Balance test and single-leg hop for distance in collegiate athletes. *J Orthop Sports Phys Ther.* 2014;44(1):A66.

45. Plisky PJ, Rauh MJ, Kaminski TW, et al. Star Excursion Balance Test as a predictor of lower extremity injury in high school basketball players. *J Orthop Sports Phys Ther.* Dec 2006;36(12):911-919.

46. Smith CA, Chimera NJ, Warren M. Association of y balance test reach asymmetry and injury in division I athletes. *Med Sci Sports Exerc.* Jan 2015;47(1):136-141.

47. Plisky PJ, Gorman PP, Butler RJ, et al. The reliability of an instrumented device for measuring components of the star excursion balance test. *N Am J Sports Phys Ther.* May 2009;4(2):92-99.

48. Krause DA, Youdas JW, Hollman JH, et al. Abdominal muscle performance as measured by the double leg-lowering test. *Arch Phys Med Rehabil.* Jul 2005;86(7):1345-1348.

49. Lanning CL, Uhl TL, Ingram CL, et al. Baseline values of trunk endurance and hip strength in collegiate athletes. *J Athl Train.* Oct-Dec 2006;41(4):427-434.

50. Butowicz CM, Ebaugh DD, Noehren B, et al. Validation of Two Clinical Measures of Core Stability. *Int J Sports Phys Ther.* Feb 2016;11(1):15-23.

51. Cohen J. *Statistical Power Analysis for the Behavioral Sciences.* New Jersey: Lawrence Erlbaum Associates, Inc.; 1988.

52. Cholewicki J, Silfies SP, Shah RA, et al. Delayed trunk muscle reflex responses increase the risk of low back injuries. *Spine (Phila Pa 1976).* Dec 1 2005;30(23):2614-2620.

53. Wilk KE, Macrina LC, Fleisig GS, et al. Deficits in Glenohumeral Passive Range of Motion Increase Risk of Shoulder Injury in Professional Baseball Pitchers: A Prospective Study. *Am J Sports Med.* Oct 2015;43(10):2379-2385.

54. Shanley E, Rauh MJ, Michener LA, et al. Shoulder range of motion measures as risk factors for shoulder and elbow injuries in high school softball and baseball players. *Am J Sports Med.* Sep 2011;39(9):1997-2006.

55. Kibler WB, Sciascia A. Current concepts: scapular dyskinesis. *Br J Sports Med.* Apr 2010;44(5):300-305.

56. Goldbeck T, Davies G. Test-retest reliability of the closed kinetic chain upper extremity stability test: a clinical field test. *Journal of Sports Rehabilitation.* 2000;9:35-45.

57. Shanley E, Thigpen CA, Clark JC, et al. Changes in passive range of motion and development of glenohumeral internal rotation deficit (GIRD) in the professional pitching shoulder between spring training in two consecutive years. *J Shoulder Elbow Surg.* Nov 2012;21(11):1605-1612.

CHAPTER FIVE: SUMMARY

This chapter presents a brief review of the rationale, specific aims, summary results, discussion, and conclusions of the aims proposed in Chapter 1. Specific aims and sub-aims will be addressed as well as each aim's limitations, conclusions, clinical relevance, and suggestions for future work. Any changes or modifications made to the original dissertation proposal will be addressed along with the rationale.

Proposed risk factors for non-contact athletic injuries include impairments in regional stability (i.e. core stability), movement pattern efficiency, mobility, and movement symmetry.[1-6] The rationale for this work is that pre-participation movement screens are gaining popularity in athletic settings to potentially identify risk factors for musculoskeletal injury and assess performance. However, the relationship between current screens, proposed risk factors, and upper extremity injury is not well understood. Currently, there is a lack of a comprehensive screening tool that assesses stability and mobility throughout the system using validated regional movement pattern control tests. Development of a reliable screen with demonstrated construct validity would provide clinicians a comprehensive assessment of proposed risk factors and possibly identify performance degradations associated with injury. *Three specific aims* presented in Chapter 1 were addressed in this dissertation: 1) describe a comprehensive performance-based movement system-screening tool for athletes, 2) determine the psychometric properties of the comprehensive performance-based movement system screen, and 3) determine the ability of the comprehensive performance-based screen to discriminate performance in athletes with and without non-traumatic shoulder injury.

Chapter 2 contains the manuscript that focused on establishing construct validity of common and novel clinical core stability tests using a convergent/ divergent validity methodological approach. This relates to *Aim 2a*. A priori hypotheses with cutoff values for correlation coefficients were used to determine construct validity of core stability tests focused on the neuromuscular control aspect of core stability. All clinical tests of core stability were validated against a lab-based biomechanical measure of core stability. This lab-based measure was considered the reference standard as it isolates neuromuscular control of the core. The manuscript in Chapter 3 focused on determining the construct validity and inter-rater reliability of the MSST screen. This relates to *Aims 2b and 2c*. Exploratory factor analysis (EFA) was used to identify clusters of latent constructs within the MSST. Once the constructs were determined, the number of tests within the screen was reduced while retaining as much of the original construct information as possible. Kappas and intraclass correlation coefficients were used to determine test item inter-rater reliability and MSST composite score inter-rater reliability, respectively. The manuscript in Chapter 4 (*Aim 3*) aimed to determine if athletes with shoulder pain demonstrated performance differences on the MSST composite score and if a subset of tests within the MSST could predict group.

Conclusions

Specific aim 1A was to identify clinical tests that demonstrate evidence of injury prediction in athletes for the core, upper and lower extremities and select a comprehensive subset of tests. The original version of the MSST was a compilation of clinical screening and rehabilitation assessments. An expansive literature search was conducted to compile clinical tests used to assess musculoskeletal injury risk, movement patterns, regional stability, mobility, and asymmetry. Tests were chosen based on current evidence and clinical practice standards (as noted by a preliminary informal panel of experts). Using a Delphi technique, experts' opinions on the value of these tests, the constructs they represent, the primary body region they represent, and the values of asymmetry were aggregated. A panel of experienced Physical Therapists with sports and/or orthopedic specialty certifications, Athletic Trainers, Certified Strength and Conditioning Specialists, and biomechanists assessed the *content validity* of the initial version of the MSST. Experts were chosen based on their experience and knowledge in orthopedic assessment. Physical Therapists with Orthopedic Specialist Certification or with Sports Specialist Certification were chosen because of their specific skills and training in assessing human movement.

The expert opinion analysis utilized a free online survey tool (Qualtrics) provided by Drexel University. An initial email (language in Appendix 10) was sent to a panel of 20 experts. The survey was designed to collect no personal or identifying information from respondents. IP addresses were not recorded. All responses were anonymous and only aggregate data was amassed. In the first round of the Delphi, experts were asked to rate their level of agreement on the current categorization of tests within the MSST, the primary region of the body the test is assessing, and if they thought asymmetry was important. The complete survey for round 1 is available in Appendix 11. Fifteen experts completed the first round of the survey. Results revealed that a majority of experts agreed on the primary region each test was assessing, the importance of asymmetry, and the test construct.

In the second round of the Delphi, experts were given the results from the previous round of questions, as well as the inter-rater reliability of items within the MSST (full survey in Appendix 12). Experts were asked to rank-order the tests within the MSST for each construct based on the results of the previous round and test reliability. Experts were reminded that the goal of the MSST is to represent all constructs (movement pattern efficiency, stability, mobility) and performance characteristics (neuromuscular control, muscle capacity) across the major regions of the body. Nine of twenty experts completed the second survey ranking tests for inclusion in the MSST. Results from the second survey revealed that experts selected 21 of the 32 original tests for inclusion in the screen. These 21 tests were used as the second version of the MSST and the version that was utilized in Specific Aim 2b for exploratory factor analysis. A breakdown of all survey results is available in Appendix 13.

Specific Aim 1a originally proposed that the second round of the Delphi would ask assess expert agreement related to the following: 1) each item's determination of testing construct: movement pattern efficiency, stability, and/or mobility, 2) each item's determination of level of current evidence-based support or pragmatic use in the clinic as a screening tool for performance and/or risk factor of injury, 3) each item's body region or regions of assessment core stability (either neuromuscular control or capacity), upper extremity, or lower extremity functional movement patterns or symmetry, 4) each item's proposed list of deviations from the expected optimum performance of the test, 5)the initial proposed scoring system based on current evidence, item performance expectations, and distribution of selected constructs, and 6) level of inter-rater agreement and test redundancy required for further modification.

Specific Aim 1a utilized a systematic approach to the development of a novel comprehensive screen specifically designed to assess proposed risk factors of injury. The results of this aim provided the framework of the MSST, which will then be further developed and validated through subsequent aims. The survey development process provided me with a new skill set to approach research questions and an experience that will assist me in future interdisciplinary work.

Specific Aim 1b was to describe newly developed clinical tests of core stability. Preliminary work of this dissertation revealed the possibility of two new clinical tests that emphasize the neuromuscular control aspect of core stability. The unilateral hip bridge endurance (UHBE) and clinical core control tests (CCCT) were developed in an attempt to clinically quantify core neuromuscular control (Figures 1A and 1B).

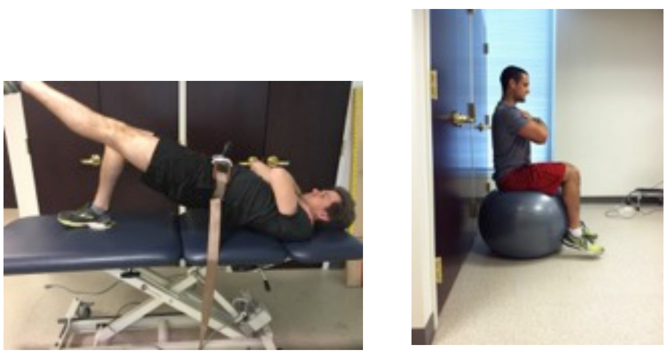


Figure 1a and 1b: 1A) Unilateral Hip Bridge Endurance requires an individual to maintain a neutral pelvis during a single-leg bridge for as long as possible. 1B) Clinical Core Control Test requires an individual to sit on a Swiss ball with the feet off from the ground in an upright posture for as long as possible.

The UHBE was adapted and standardized from previous work by Miller et al which utilized this test as a test of gluteal muscle endurance and Okubo et al which suggested the unilateral hip bridge requires significant activation of lumbopelvic complex stabilizing musculature.[7,8] We developed this test in an effort to assess both muscle capacity and neuromuscular control of the core musculature (trunk, pelvis, and proximal lower extremity). Without knowledge of how the test was previously performed, we developed a standardized protocol through pilot testing. Data analysis revealed a large variance in performance between trials; therefore, we implemented a standardized practice trial with feedback from the examiner as well as a coefficient of variation qualification. In an attempt to stabilize the data, we used the coefficient of variation to assess the variance between trials. Using 15% coefficient of variation between trials as the cut point, if the first two trials on each side were less than the cut point, then a third trial was not performed.

The CCCT was developed as a clinical version of our lab-based measure of core stability. The lab-based measure was designed to assess the neuromuscular control aspect of core stability and has been able to identify trunk neuromuscular control impairments in patients with low back pain.[9-11] The lab measure uses seated balance tasks that isolate core neuromuscular control by minimizing influence from the upper and lower extremities. The variables associated with this measure provide quantifiable data regarding an individual's ability to control the motion and position of the trunk and pelvis during static and dynamic tasks. Recently, Noehren et al presented a novel clinical test to assess the neuromuscular control aspect of core stability.[12] A study performed in our lab and subsequently published[13] revealed that the test presented in Noehren et al (2014) was not correlated to our lab-based measure, and therefore not a valid assessment of isolated core neuromuscular control. Based on these results, we developed the CCCT. Preliminary analysis on a small subset of healthy adults and athletes (N = 16) suggested a moderate to large significant correlation between the CCCT and the lab-based measure of core stability. We developed a standardized testing protocol through pilot work and utilized the same data stabilizing methods as were used for the UHBE.

Specific aim 2a was to determine construct validity of the clinical tests of core stability by validating these screening items (9 tests) within the MSST against static and dynamic lab-based measures of core stability in a sample of Division 1 and professional athletes. This study used correlational analyses to determine the relationship between clinical and lab-based measures of core neuromuscular control. The lab-based measures utilized seated balance tasks that isolated core neuromuscular control by minimizing influence from the upper and lower extremities. These tests consisted of static trunk control (eyes open) and dynamic trunk control utilizing a specially designed target acquisition task. Core neuromuscular control was quantified using center of pressure (COP) measures derived from force plate data (Figure 2A, 2B, 2C).

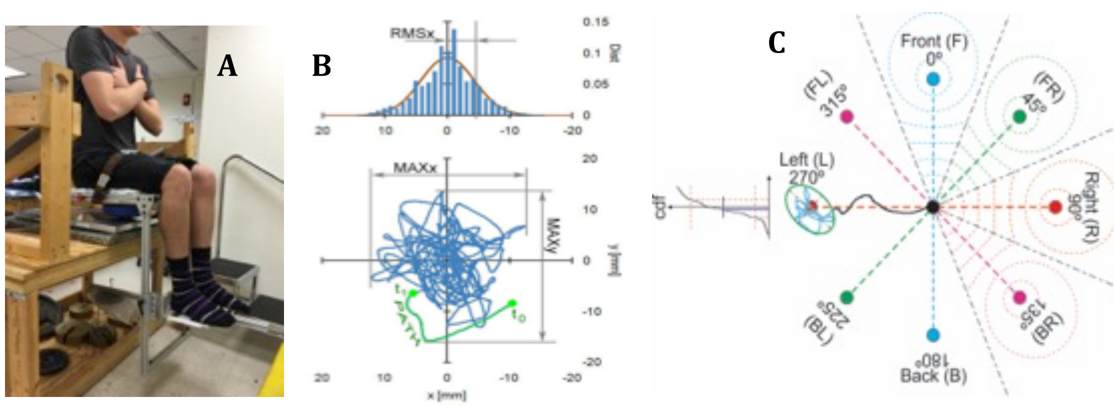


Figure 2. A) Subject set up on chair: this setup reduces influence of the lower extremities by strapping the legs together and supporting the feet on a footplate that is attached to the chair. This eliminates control of the chair through the lower extremities. B) COP information from force plate data allow us to quantify performance using the 95% confidence ellipse area and mean velocity of the center pressure during static balance. C) This is an illustration of the target acquisition test orientation and directional control variables associated with the test. Directional control is measured by the excursion of the COP to and from the target and the amount of movement around the target.

Using a convergent and divergent validity approach, performance on clinical measures assumed to assess the neuromuscular control and muscular capacity aspects of core stability were evaluated against a lab-based measure of isolated core neuromuscular control. A priori, we considered any correlation greater than or equal to 0.3, a medium or moderate effect according to Cohen [14], as a clinically important relationship. Other studies have used a 0.4 cutoff value to determine convergent and divergent validity.[15] However, we chose a cutoff of 0.3 because clinical tests of core stability often do not isolate control of the trunk and pelvis and thus there are potentially other regions of the body involved that could affect task performance.

The results demonstrated significant small correlations ($r_s < 0.3$, $p < 0.05$) between the clinical core control test (CCCT), trunk extensor endurance (EXT), trunk stability push-up (TSPU) and dynamic directional control (DCMVEL). There were also significant small correlations ($r_s < 0.3$, $p < 0.05$) between the trunk flexor endurance (FLEX), side bridge with active hip abduction (SBAHA), rotary stability (RS) and dynamic precision control (PCCEA). None of the clinical measures of core stability tests assumed to emphasize neuromuscular control demonstrated acceptable convergent validity (0.3 or greater correlation to the lab-based measure of neuromuscular control). We hypothesized that the FLEX, EXT, and double-leg lowering (DLLT) tests would not reach a level of moderate and significant correlation with the lab-based measure because the lab measure assumedly is primarily assessing neuromuscular control while these tests assess core muscle capacity. Our hypotheses were confirmed (3/3), as above-mentioned tests had correlational values less than 0.3 (divergent validity), thus supporting their assessment of a different construct than the lab measure.

This study assessed two clinical tests of core neuromuscular control that were developed in *specific aim 1b*. The unilateral hip bridge (UHBE) and CCCT have demonstrated moderate significant relationships to the lab-based measure in healthy young adults during preliminary work.[13] These tests were included in this study to determine their validity as clinical core stability tests in an athletic population. Results demonstrated a small significant correlation between the CCCT and DCMVEL, explaining approximately 7% of the variance in DCMVEL. While the CCCT was designed as a clinical version of the lab-based measure, it appears that the CCCT may not be an adequate clinical assessment of the neuromuscular control aspect of core stability in athletes. The lack of a moderate correlation between the lab-based measures and the CCCT may be explained by the influence of bodyweight and height of the athlete on CCCT performance. The ball deforms based on bodyweight, creating a larger surface area in contact with the ground, thus changing the demands of the task. However, in the lab measures, the surface area of the chair contact with the force plate remains constant between subjects.

Trunk length and leg length may have also affected performance on the ball based on an individual's mass distribution. Individuals with longer trunk lengths have a higher center of mass, which may increase the challenge of the task. However, we assumed this challenge is similar between the clinical and lab measures. Leg length may have influenced performance, as individuals with longer legs may have had to assume a more flexed hip position. This may have resulted in the trunk and/or pelvis being out of a neutral position, potentially making it more challenging for a subject to maintain their balance. This differs from the lab-based measure because the set up of the lab measure allows for preservation the 90-90 positions of the hips and knees. Therefore, anthropometric differences potentially create an opposite effect on these two tests, as the ball deformation makes the tasks easier for the clinical tests, but greater weight and trunk length on the lab test make the task harder. While the CCCT demonstrates face validity, it lacks construct validity in this sample of athletes.

Previous work demonstrated a moderate significant correlation between the UHBE and the static lab-based measures of core stability.[13] In the sample of athletes (N = 55) used in this study, however, results did not demonstrate a moderate or significant correlation ($r_s \leq 0.15$) between the UHBE and either static or dynamic lab-based measures of core stability. A possible explanation for the lack of relationship may be that the testing protocol in the current study was considerably longer and involved more tests of core stability than previous work. While we attempted to control for fatigue by incorporating standardized rest times, many of the tests required use of the same muscle groups and therefore muscle fatigue may have been inevitable.

Our findings suggest that clinical tests used in this study are measuring constructs different than that of static and dynamic lab-based measures of isolated core neuromuscular control. The clinical tests used in this study were chosen based on expert opinion (assessed via a Delphi panel) and current evidence; however, they do not represent all possible clinical assessments of core stability. Certain clinical tests used (AHA, SBAHA, RS, and TSPU) were scored on a 0-3 ordinal scale. Therefore a possible lack of variance among the data may have influenced results.[16] This study used athletes 18-35 years of age and thus the findings may not be generalizable to individuals outside of this age range or outside of our definition of an athlete. Future work should be done to better understand the utility of these clinical tests in athletes as well as further development of clinical tests of isolated core neuromuscular control.

Specific Aim 2b was to determine screen constructs and inter-rater reliability of tests within the comprehensive performance-based movement system screen. Using a cross-sectional design, eighty-one collegiate and professional athletes completed the 21 (33 variables, given bilaterally scoring) different clinical tests within the MSST (see *specific aim 1a*). These tests were proposed to assess movement pattern efficiency, stability, mobility, and asymmetry of movement in the core, upper, and lower extremities. Exploratory factor analysis (EFA) was performed in order to identify constructs within the MSST. Inter-rater reliability was determined based on test scores of two independent, experienced raters.

Forty of the subjects in this study had a current episode of shoulder pain, as this study was part of a larger study assessing the relationship between non-traumatic shoulder injuries and core stability in athletes. None of the subjects with shoulder pain performed the closed kinetic chain upper extremity stability test (CKCUEST). Furthermore, all subjects completed a pain rating scale (/10 points) after each test. If any test caused a 2-point increase on the pain rating scale, the session was terminated. All subjects completed the testing protocol without any reported increased pain.

Tests were examined for EFA appropriateness via the Kaplin-Meyer-Olkin (KMO) measure of sampling adequacy, Bartlett's test of sphericity, and the anti-image correlation matrix. Once tests with unacceptable sampling adequacy (anti-image matrix value <0.5) were removed, the EFA with and without factor rotation was completed.

Factors with eigenvalues greater than 1.0 were extracted while test communalities within each factor were suppressed at 0.4.

Two raters independently assessed each subject's performance on the MSST. Raters included an exercise scientist (one of the screen developers) and a physical therapist with a Sports Specialist Certification. Inter-rater reliability was not performed on all tests. Tests that could be scored by both raters concurrently (i.e. squat) were used to assess inter-rater reliability. Tests that would have required the subject to repeat the test performance (i.e. Y-Balance Test) were not included in this analysis due to time constraints. It should be noted that the 20-minute screen was part of a larger study protocol that lasted about two hours. For those tests that required a quantitative measurement, the primary rater took the measurement and the secondary rater confirmed the measured value. Detailed descriptions of MSST test performance and how the tests were to be scored are presented in Table 1 of Chapter 3. Cohen's kappa was used to determine rater agreement for individual tests within the MSST. Inter-rater agreement of tests were interpreted according to Landis and Koch [<0: no agreement, 0.1-0.20: slight agreement, 0.21-0.40: fair agreement, 0.41-0.60: moderate agreement, 0.61-0.80: substantial agreement, 0.81-0.99: almost perfect agreement].[17]

The KMO (0.58) and Bartlett's test ($p = 0.001$) found 24 variables (representing 15 different tests) within the screen were appropriate for EFA. Examination of individual KMO statistics within the anti-image correlation matrix revealed that the following 9 tests did not have adequate sampling adequacy: left side bridge with hip abduction, modified Thomas test, left and right in-line lunge, trunk stability push up, trunk extensor endurance, trunk flexor endurance, clinical core control test, and left scapular dyskinesis and as such they were eliminated from the analysis. Thus, 15 tests, many of which were scored independently for the left and right side, were analyzed.

Results demonstrated that the EFA revealed 7 factors (factors with Eigenvalues greater than 1.0), which represented 63% of the variance accounted for (VAF). The construct of movement pattern efficiency (MPE), representing 21.3 % VAF, loaded on two factors (lower extremity MPE with trunk/pelvis stability required and lower extremity dynamic MPE). The construct of regional stability represented 24.8% VAF loading on three factors (upper and lower extremity stability; trunk and pelvis stability; trunk and pelvis stability with extremity movement). The construct of mobility represented 16.8% VAF, loading on two factors (upper and lower extremity mobility; trunk mobility). For details see factor structure in Table 4 in Chapter 3. Inter-rater reliability for the individual MSST tests are presented in Table 5 in Chapter 3.

The factors of the EFA capture three constructs of the MSST (movement pattern efficiency, stability, and mobility). Each construct is primarily represented by one or two body regions: movement pattern efficiency (lower extremity, dynamic lower extremity), regional stability (upper and lower extremity, trunk/pelvis, dynamic), and mobility (upper and lower extremity, trunk/pelvis). Combined, these 7 factors explain 62.9% of the variance in the MSST. This finding suggests that these factors represent and validate the constructs within the MSST.[18]

As part of the analysis we examined the factor structure when a Varimax rotation was applied. Varimax rotation produced 8 factors, explaining 67% of the variance. The 8 factors produced represent the same constructs as the original analysis; however, the rotation further grouped some constructs by region. For example, extremity mobility became two separate factors, upper extremity mobility and lower extremity mobility. This level of detail may be useful in future work if the MSST is divided into extremity dependent subsets, such as an upper extremity screen for use in upper extremity dominant sports.

Currently, the MSST takes approximately 20 minutes to screen an individual. Optimally, we believe that screens should be completed in less than 10 minutes per person. Therefore, there may be value in the development of a subset if extremity dependent or sport specific screens. These subset screens would retain the constructs of movement pattern efficiency, stability, and mobility while being expedient.

The MSST tests included tests used within other published athletic screens as well as tests based on the expert opinions. The current study investigated the test inter-rater reliability of qualitative assessments (e.g. squat) rather than quantitative assessments (e.g. single-leg hop) as the quantitative tests would have required repeat performances, which would have increased the duration of the testing protocol and likely induced subject fatigue. In addition, all quantitative tests in the MSST have established reliability, with the exception of the UHBE.[19-25] Individual test inter-rater reliability ranged from slight to almost perfect agreement (k = 0.26 – 0.97), with one test demonstrating 100% agreement between raters (lack of variance in data did not allow for kappa computation). The slight agreement between raters on the side bridge with active hip abduction test may have been due to rater location. The primary raters hand was in contact with the subjects' pelvis during the task to assess off plane pelvic motion. The second rater only visually assessed all motion 1-2 meters away. The location and contact between the primary rater and the subject may provide an explanation for the lower item reliability.

This study utilized a systematic approach to developing a comprehensive pre-participation screening tool for athletes based upon proposed risk factors for injury. The use of a Delphi technique and exploratory factor analysis to develop and validate an athletic screening tool represents an important first step to validating the tool for clinical use. This study is not without limitations. Because the screen was administered as part of a larger study, inter-rater reliability was not studied on every test within the screen. This may limit our inter-rater reliability of the composite score. However, because the tests that were not assessed by two raters have published reliability, this may mitigate this limitation. It is recommended that studies utilizing EFA typically have sample sizes of at least 100. MacCallum et al (1999) suggest that communalities in the 0.5 range should have sample sizes of at least 100; however, the minimum sample size to variable ratio depends on the study design.[26] Lawley and Maxwell (1971) suggest 51 more cases than the number of variables is acceptable in factor analysis, in which case our data meet the criteria.[27]

Several tests considered to be valuable by expert clinicians were not included in the EFA because they did not meet the statistical inclusion criteria. Removal of the modified Thomas Test may have eliminated isolated assessment of anterior lower extremity mobility. Removal of the trunk flexor and extensor endurance tests may have eliminated isolated trunk muscle capacity assessment. While these are isolated assessments of the aforementioned regions, other tests (e.g. overhead squat and unilateral hip bridge) within the screen may indirectly assess these constructs within these regions. To date, no test-retest reliability is available for the MSST. Therefore, the minimal detectable change and standard error are currently unknown. Future work should assess test re-test reliability as well as inter-rater reliability using raters with varying degrees of clinical experience. The scoring system of the MSST has not yet been validated. Further work needs to be done to validate the composite score and individual test-item scores. While our data achieved minimally acceptable sampling adequacy for EFA, the small sample size may have influenced factor loading. Future research efforts should include amassing a larger database of MSST scores from athletes and also expanding work to include military personnel.

Specific Aim 2c was to determine inter-rater reliability of the composite score on a modified version (developed based on results of Aims 1, 2a, 2b) of the comprehensive performance-based movement system screen in a cohort of athletes. For MSST composite score inter-rater reliability, each test within the MSST was scored on a 4-point scale (0-3) and summed by rater for each subject with a maximum score of 72. Intraclass correlation coefficient was used to determine inter-rater reliability of the composite score of the MSST. ICCs were interpreted according to Portney and Watkins [< 0.40: poor reliability, 0.41 – 0.74: moderate reliability, > 0.75: excellent reliability].[18] All statistical analyses were conducted using Statistical Package for the Social Sciences (version 22.0; SPSS Inc, Chicago, IL).

Results revealed that inter-rater reliability of the composite MSST score was ICC (2,1) = 0.94, 95% CI (0.91, 0.96). Composite score inter-rater reliability was excellent (ICC 2,1 = 0.94). However, this could be slightly inflated, as over half of the test items that went into the composite score were not assessed independently (as discussed in specific aim 2b). However, most of the qualitative assessments reported almost perfect inter-rater agreement and the qualitative assessments used the same scoring criteria, regardless of rater. The excellent composite score reliability is promising for clinical implementation.

Specific Aim 3a was to assess the ability of the MSST to discriminate performance differences between athletes with and without non-traumatic shoulder pain. The closed kinetic chain upper extremity stability test (CKCUEST) was included as part of the MSST as per the Delphi expert panel analysis (see *Aim 1*) and results of an exploratory factor analysis (see *Aim 2b*). In an attempt to protect athletes with current shoulder pain from further potential injury, this test was not performed on this group. The statistical analysis was first performed with a CKCUEST score of zero being assigned to subjects with shoulder pain (max composite score of 75). However, it is impossible to know if all athletes with current shoulder pain would have received a zero score on this test. Therefore, to reduce potential bias of this approach, a second analysis was performed with the CKCUEST score removed from the composite score for all subjects. The validation with known groups results demonstrated that athletes with non-traumatic shoulder pain (composite score = 56.6 ± 5.8) scored significantly lower than healthy athletes (composite score = 62.17 ± 4.7) on the MSST with the CKCUEST included ($t = 4.74$, $p < 0.001$, $d = 1.05$). A large effect size was achieved with a mean difference between groups of 5.6 points. Analysis of the influence of the CKCUEST inclusion revealed no differences in the results of the t-test. The results of the t-test remained statistically significant when the CKCUEST was removed (shoulder pain group mean = 56.6 ± 5.8, control group mean = 59.5 ± 4.8, $t = 2.43$, $p = 0.02$, $d = 0.54$). The mean difference between groups was 2.9 points.

The significant difference in composite MSST scores in athletes with and without non-traumatic shoulder pain and calculated effect size (d = 0.54) suggests that athletes with shoulder pain demonstrate impairments within the movement system associated with the presence of pain. Only 10% of athletes with shoulder pain reported pain (received a score of zero) during performance of any upper extremity test. This low percentage suggests that pain with movement was not the primary factor driving the lower composite score in these athletes. However, because we utilized a known groups approach, it is unknown to what extent the pain group's current pain levels may have affected their overall performance. Since athletes in the pain group had a current shoulder injury, they may have developed compensatory movement strategies in order to avoid pain. However, only one athlete reported pain at rest, which did not increase during the protocol.

The MSST was designed as a comprehensive screen to assess regional stability, movement pattern efficiency, mobility, and movement symmetry in all body regions. The MSST attempts to address limitations of other published screens by including tests focused to core stability (e.g. unilateral hip bridge endurance and double-leg lowering test) and upper extremity movement pattern efficiency and/or stability tests (e.g. scapular dyskinesis and CKCUEST). Based on the kinetic chain model, performance degradations within any of these constructs may lead to breakdowns within the chain and potentially increase injury risk and/or hinder athletic performance. While each of these constructs is a proposed injury risk factor, their relationship to non-traumatic upper extremity injury is not fully understood. Evidence supports the relationship between impaired performance within these constructs and lower extremity and low back injury; yet, a paucity of evidence exists in relation to upper extremity injury.[6,28-32] The ability of the MSST to identify known groups with and without an upper extremity injury provides preliminary support for its use to predict shoulder injury pre-season. Future studies need to be conducted to determine the MSST's ability to predict upper extremity injuries in athletes. Additionally, future studies should determine the ability of the MSST to predict lower extremity and low back athletic injuries.

Specific Aim 3b was to identify items in the modified comprehensive performance-based movement system screen that optimally classify athletes with and without non-traumatic shoulder pain. Logistic regression was conducted to assess whether the potential predictor tests of RS bilaterally, SHOMOB-dominant, and GIRD also significantly predicted whether or not an athlete had shoulder pain. These variables were chosen because they independently demonstrated significant ($p<0.1$) differences between groups. When considered together, these tests significantly predict whether or not an athlete had shoulder pain 69% of the time, $\chi^2 = 14.37$, df = 5, N = 81, p = 0.01. Dominant arm shoulder mobility was the only variable with a significant odds ratio (OR: 0.38, p = 0.05, 95% CI: 0.15, 1.00).

Collectively the, rotary stability, GIRD, and dominant arm shoulder mobility tests were able to accurately predict the injured group in 69% of all cases. This subset of MSST tests has face validity as rotary stability is assessing core stability with upper extremity motion while GIRD is assessing internal rotation and shoulder mobility is assessing external rotation and abduction of the shoulder. These tests represent core stability and mobility, which are two proposed risk factors for upper extremity injury. The results of the logistic regression suggest that the odds of an athlete having shoulder pain are increased as dominant arm shoulder mobility performance decreases and when

GIRD is present. Deficits in shoulder range of motion have been associated with shoulder injury in overhead athletes.[32,33] The findings of the current study support this association, as athletes with a current shoulder injury were more likely to have poorer scores on shoulder range of motion tests. Rotary stability, shoulder mobility, and GIRD could potentially be used as a subset of tests to predict upper extremity injuries in athletes. However, future studies should also include CKCUEST in the subset as previous work has demonstrated this test is associated with development of shoulder pain in football players.[34]

Limitations

The approach used to develop the MSST utilized an extensive literature search and preliminary expert panel followed by a Delphi approach and then an exploratory factor analysis. Though this is the first study to develop a movement system screen through this form of a systematic approach, it does not come without limitations. The tests selected for the initial version of the screen (*Aim 1a*) was a combination of tests compiled from current evidence and clinical expertise of a preliminary panel of experts. While we attempted for this list of tests to be exhaustive, it is possible that a different preliminary panel of experts may have chosen to include different tests based on their experience and expertise. Two members of the preliminary panel were also a part of the Delphi and as such there responses in the Delphi may have been biased based on their involvement in the original development. However, because the responses in the Delphi were anonymous, it is unknown whether these experts submitted responses in the Delphi. The twenty experts that were chosen as experts in the Delphi approach were a combination Physical Therapists with sports and/or orthopedic specialty certifications, Athletic Trainers, Certified Strength and Conditioning Specialists, and biomechanists. While we attempted to procure responses from experts in each of these specialties, it is possible that there may have been more responses from one specialty than another, which may have influenced results.

One objective of this dissertation was to validate clinical tests of core stability against our lab-based measure. The lab-based measure used in this dissertation is assumed to represent the gold standard of assessing the neuromuscular control aspect of core stability. The protocols and variables used in the lab-based measure have been validated in low back patients, yet this this is the first study to use these measures to assess core stability in athletes. The protocol for the lab-based measure requires six familiarization trials followed by six static trials (3 eyes open, 3 eyes closed) and then four dynamic trials. These procedures were conducted prior to performance of all clinical tests of core stability (9 tests). These nine tests were part of a larger battery tests within the MSST and were performed in a manner in which would optimize protocol flow within the lab. Based on the kinetic chain model, core stability is required for the sequential coordination energy generation, transfer, and dissipation between segments. It follows then that the core musculature may have been involved in tests other than the tests designed to assess core stability. Therefore, even though we attempted to control for fatigue by incorporating standardized rest times between tests and utilized a Borg scale to assess perceived exertion, subject fatigue may have influenced results.

This dissertation attempted to determine the construct validity of the MSST through an exploratory factor analysis (EFA). EFA is a statistical approach to identifying similar constructs within a measure and typically is suggested to require a minimum of

100 to 200 subjects. However, minimum sample size has been suggested to be dependent on study design and may be sufficient when there are 51 more cases than the number of variables, in which case our data meet the criteria.[27] Considering our data met the criteria for Bartlett's test of sphericity and the minimal KMO (0.5), it is possible that more subjects may serve to increase the KMO statistic and further strengthen the factor structure.

As one of the objectives of this dissertation was to develop a novel comprehensive screen, another objective was to determine the inter-rater reliability of the screen. Due to time constraints from the overall protocol length (approximately two hours), we chose to only assess inter-rater reliability on tests that were scored qualitatively (i.e. squat). The quantitative tests (i.e. single-leg hop) would have required repeat performances, which would have increased the duration of the testing protocol and likely induced subject fatigue. In addition, all quantitative tests in the MSST have established reliability, with the exception of the UHBE.[19-25] The lack of inter-rater reliability for some tests within the sample of athletes used in the current study may have affected MSST composite score reliability. This study analyzed inter-rater reliability using the kappa statistic, including some values that could not be computed due to 100% agreement between raters. We used a dichotomous approach, analyzing whether raters did or did not observe a deviation and then again analyzing if it was the same deviation. Through recent discussion within the lab, it has been suggested to use a weighted kappa approach to determine the level of agreement between raters regarding the amount of deviation observed, as this method may be a more accurate measure of ordinal level data.

I intend to re-analyze the data using this new approach in an effort to further understand the reliability of the MSST.

The objective aimed at determining the ability of the MSST to discriminate performance differences between athletes with and without non-traumatic shoulder pain may have been limited by the study design. This study utilized a known groups approach and so it is not known if the MSST composite score can predict which athletes will sustain a shoulder injury or which athletes are more at risk. To date, the test-retest reliability of the MSST is unknown; therefore we cannot say that the group differences in the current study would exceed the minimal detectable change (MDC) of the MSST.

Implications for Rehabilitation

The results of this dissertation have significant implications for rehabilitation. The results of the EFA validate that the MSST assesses the constructs movement pattern efficiency, stability, and mobility. This validation will provide clinician's a screening tool that directly assesses these constructs; all proposed risk factors for musculoskeletal injury. By scoring each bilateral test independently, clinicians may be able to determine asymmetries, another proposed risk factor for injury. The ability of the MSST to discriminate performance differences between athletes with and without non-traumatic shoulder pain preliminarily suggests the MSST may be useful as a pre-participation screen for athletes. Results of the logistic regression may provide clinicians a subset of tests for use in overhead athletes. Potential subset screens can retain the constructs of movement pattern efficiency, stability, and mobility while being field-expedient. Though no clinical test of core stability was determined to primarily assess the neuromuscular control aspect of core stability in this sample, the findings of this study support the hypothesis that tests of muscle capacity are measuring different constructs than neuromuscular control. While preliminary work supported the use of two novel clinical tests of core neuromuscular control, the results of this study do not support their individual use in an athletic population for determining core neuromuscular control.

Recommendation for future studies

This study was designed to systematically develop a comprehensive movement system screen based on proposed risk factors of injury, determine the psychometric properties of the screen, and determine it's ability to discriminate performance differences in athletes with and without non-traumatic shoulder pain. However, a major limitation of this study is that we do not have test-retest reliability of the MSST. Thus, we do not know if the performances differences between groups exceed the screen's MDC. The next step in the MSST development is to determine test-retest reliability and the 90% MDC in athletes. This test-retest study to determine the measurement properties of the MSST should be done prior to the execution of a prospective study as this information will determine if performance differences reflect true differences and not random measurement error. The current study did not establish the ability of the MSST's to predict injury risk. The next step in the screen development is a prospective design to determine the screen's ability to accurately predict injury in athletic and military populations. This injury prediction capability relative to traditional athletes will occur as a multi-site study at several universities. The injury prediction capability in the military population will develop through contact during my postdoctoral work at Walter Reed. From this approach, receiver operating characteristic curves (ROC) and diagnostic accuracy could be used to determine cut points for injury prediction.

This study also aimed at validating common and novel clinical tests of core neuromuscular control. The findings of this study suggest that none of the clinical tests used were assessing core neuromuscular control. One possible explanation for this is that these tests were conducted as part of a larger protocol and as such, fatigue may have affected performance. Future studies should attempt to limit the number of clinical tests used to reduce fatigue of muscle groups that are required for all tests. As previous work has suggested the UHBE is a valid test of core neuromuscular control in healthy adults[13], future work should assess the inter-rater and test-retest reliability of the measure.

REFERENCES

1. Leetun DT, Ireland ML, Willson JD, et al. Core stability measures as risk factors for lower extremity injury in athletes. *Med Sci Sports Exerc.* Jun 2004;36(6):926-934.

2. Liemohn WP, Baumgartner TA, Fordham SR, et al. Quantifying core stability: a technical report. *J Strength Cond Res.* 2010;24(2):575-579.

3. Kibler WB, Press J, Sciascia A. The role of core stability in athletic function. *Sports Med.* 2006;36(3):189-198.

4. Hewett TE, Myer GD, Ford KR, et al. Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: a prospective study. *Am J Sports Med.* Apr 2005;33(4):492-501.

5. Aguinaldo AL, Buttermore J, Chambers H. Effects of upper trunk rotation on shoulder joint torque among baseball pitchers of various levels. *J Appl Biomech.* Feb 2007;23(1):42-51.

6. Zazulak BT, Hewett TE, Reeves NP, et al. Deficits in neuromuscular control of the trunk predict knee injury risk: a prospective biomechanical-epidemiologic study. *Am J Sports Med.* Jul 2007;35(7):1123-1130.

7. Miller MM, Grooms D, Schussler E, et al. Single Leg Glute Bridge: A Clinical Test for Gluteal Muscle Endurance. *Med Sci Sports Exerc.* 2013;45(5):430-430.

8. Okubo Y, Kaneoka K, Imai A, et al. Electromyographic analysis of transversus abdominis and lumbar multifidus using wire electrodes during lumbar stabilization exercises. *J Orthop Sports Phys Ther.* Nov 2010;40(11):743-750.

9. Cholewicki J, Simons AP, Radebold A. Effects of external trunk loads on lumbar spine stability. *J Biomech.* Nov 2000;33(11):1377-1385.

10. Radebold A, Cholewicki J, Polzhofer GK, et al. Impaired postural control of the lumbar spine is associated with delayed muscle response times in patients with chronic idiopathic low back pain. *Spine (Phila Pa 1976).* Apr 1 2001;26(7):724-730.

11. Sung W, Abraham M, Plastaras C, et al. Trunk motor control deficits in acute and subacute low back pain are not associated with pain or fear of movement. *Spine J.* Aug 1 2015;15(8):1772-1782.

12. Noehren B, Abraham A, Curry M, et al. Evaluation of proximal joint kinematics and muscle strength following ACL reconstruction surgery in female athletes. *J Orthop Res.* Oct 2014;32(10):1305-1310.

13. Butowicz CM, Ebaugh DD, Noehren B, et al. Validation of Two Clinical Measures of Core Stability. *Int J Sports Phys Ther.* Feb 2016;11(1):15-23.

14. Cohen J. A power primer. *Psychol Bull.* Jul 1992;112(1):155-159.

15. Tveter AT, Dagfinrud H, Moseng T, et al. Measuring health-related physical fitness in physiotherapy practice: reliability, validity, and feasibility of clinical field tests and a patient-reported measure. *J Orthop Sports Phys Ther.* Mar 2014;44(3):206-216.

16. Portney LG, Watkins MP. *Foundations of Clinical Research: Applications to Practice.* 3rd ed ed. Upper Saddle River, NJ: Prentice Hall; 2009.

17. Landis JR, Koch GG. The measurement of observer agreement for categorical data. *Biometrics.* Mar 1977;33(1):159-174.

18. Portney LG, Watkins MP. *Foundations of Clinical Research: Applications to Research.* Third Edition ed. New Jersey: Pearson Education, Inc.; 2009.

19. Krause DA, Youdas JW, Hollman JH, et al. Abdominal muscle performance as measured by the double leg-lowering test. *Arch Phys Med Rehabil.* Jul 2005;86(7):1345-1348.

20. Munro AG, Herrington LC. Between-session reliability of four hop tests and the agility T-test. *J Strength Cond Res.* May 2011;25(5):1470-1477.

21. Plisky PJ, Gorman PP, Butler RJ, et al. The reliability of an instrumented device for measuring components of the star excursion balance test. *N Am J Sports Phys Ther.* May 2009;4(2):92-99.

22. Onate JA, Dewey T, Kollock RO, et al. Real-time intersession and interrater reliability of the functional movement screen. *J Strength Cond Res.* Feb 2012;26(2):408-415.

23. Goldbeck T, Davies G. Test-retest reliability of the closed kinetic chain upper extremity stability test: a clinical field test. *Journal of Sports Rehabilitation.* 2000;9:35-45.

24. McClure P, Tate AR, Kareha S, et al. A clinical method for identifying scapular dyskinesis, part 1: reliability. *J Athl Train.* Mar-Apr 2009;44(2):160-164.

25. Kevern MA, Beecher M, Rao S. Reliability of measurement of glenohumeral internal rotation, external rotation, and total arc of motion in 3 test positions. *J Athl Train.* Sep-Oct 2014;49(5):640-646.

26. MacCallum R, Widaman K, Zhang S, et al. Sample size in factor analysis. *Psychol Methods.* 1999;4(1):84-89.

27. Lawley DN, Maxwell AE. *Factor analysis as a statistical method.* American Elsevier Pub. Co.; 1971.

28. Chorba RS, Chorba DJ, Bouillon LE, et al. Use of a functional movement screening tool to determine injury risk in female collegiate athletes. *N Am J Sports Phys Ther.* Jun 2010;5(2):47-54.

29. Cholewicki J, Silfies SP, Shah RA, et al. Delayed trunk muscle reflex responses increase the risk of low back injuries. *Spine (Phila Pa 1976).* Dec 1 2005;30(23):2614-2620.

30. Plisky PJ, Rauh MJ, Kaminski TW, et al. Star Excursion Balance Test as a predictor of lower extremity injury in high school basketball players. *J Orthop Sports Phys Ther.* Dec 2006;36(12):911-919.

31. Mokha M, Sprague PA, Gatens DR. Predicting Musculoskeletal Injury in National Collegiate Athletic Association Division II Athletes From Asymmetries and Individual-Test Versus Composite Functional Movement Screen Scores. *J Athl Train.* Jan 21 2016.

32. Wilk KE, Macrina LC, Fleisig GS, et al. Deficits in Glenohumeral Passive Range of Motion Increase Risk of Shoulder Injury in Professional Baseball Pitchers: A Prospective Study. *Am J Sports Med.* Oct 2015;43(10):2379-2385.

33. Shanley E, Rauh MJ, Michener LA, et al. Shoulder range of motion measures as risk factors for shoulder and elbow injuries in high school softball and baseball players. *Am J Sports Med.* Sep 2011;39(9):1997-2006.

34. Pontillo M, Spinelli B, Sennett B. Prediction of in-season shoulder injury from preseason testing in Division I collegiate football players. *Sports Health.* 2015;6(6):497-503.

Appendices

Appendix 1.

Double-Leg Lowering Test

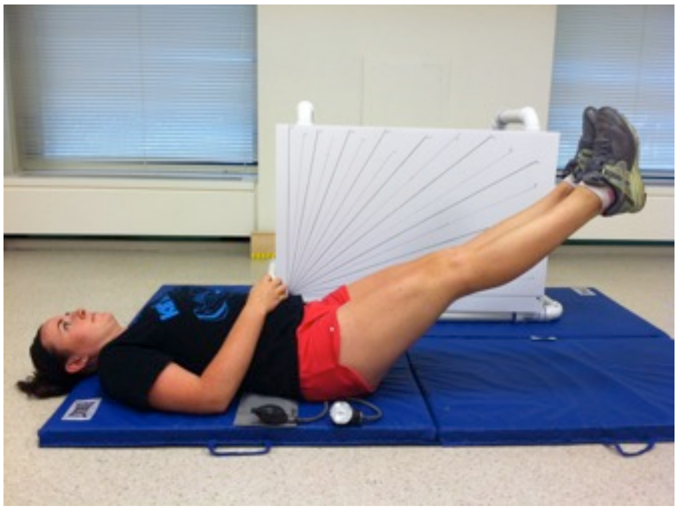


Figure 13. Double-leg lowering test

Appendix 2.

Table 6. Expert panel demographics

Initials	Years Experience	Certifications/Training
JO	8	PT, DPT, OCS, FMS, SFMA
ST	8	PT, DPT, OCS, FMS
SS	28	PT, PhD
DE	26	PT, PhD
JO	18	PhD, AT, ATC, FNATA
NG	12	PT, DPT, OCS, CSCS
CB	10	MSEd, CSCS
MP	11	PT, DPT, SCS

Appendix 3.

MSST Data Collection Sheets

Legacy Fund Clinical Core

Date:
Subject #
TT **RT**

Side Bridge Series

Test		**Pain**	**Deviation**	**Where**	**NT**	**Symmetry**
Active Hip ABD	**L**	N ☐ Y☐	NA☐ S☐ O☐	Pelvis/Trunk □ Hip □	☐	
Comments: **Full AROM Yes ☐ No ☐**						
Active Hip ABD resist	L	N ☐ Y☐	NA☐ S☐ O☐	Pelvis/Trunk □ Hip □	☐	
Comments:						
Side Bridge	R	N ☐ Y☐	NA☐ S☐ O☐	Pelvis/Trunk □ Hip □	☐	
Comments:						
Side Bridge-hip ABD	R	N ☐ Y☐	NA☐ S☐ O☐	Pelvis/Trunk □ Hip □	☐	
Comments:						
Side Bridge-hip ABD-R	R	N ☐ Y☐	NA☐ S☐ O☐	Pelvis/Trunk □ Hip □	☐	
Comments:						

Active Hip ABD	**R**	N ☐ Y☐	NA☐ S☐ O☐	Pelvis/Trunk □ Hip □	☐	Y □ N□ Worst side? R or L
Comments: **Full AROM Yes ☐ No ☐**						
Active Hip ABD-R	R	N ☐ Y☐	NA☐ S☐ O☐	Pelvis/Trunk □ Hip □	☐	Y □ N□ Worst side? R or L
Comments:						
Side Bridge	L	N ☐ Y☐	NA☐ S☐ O☐	Pelvis/Trunk □ Hip □	☐	Y □ N□ Worst side? R or L
Comments:						
Side Bridge-hip ABD	L	N ☐ Y☐	NA☐ S☐ O☐	Pelvis/Trunk □ Hip □	☐	Y □ N□ Worst side? R or L
Comments:						
Side Bridge-hip ABD-R	L	N ☐ Y☐	NA☐ S☐ O☐	Pelvis/Trunk □ Hip □	☐	Y □ N□ Worst side? R or L
Comments:						

Legacy Fund Clinical Core

Date:
Subject #
TT **RT**

Supine Series

Test		Pain	Deviation	Where		NT	Symmetry
Thomas Test	L	N ☐ Y☐	No □ Yes □	+ Rectus ☐ + Psoas ☐		☐	Y □ N□ Worst side? R or L
	R	N ☐ Y☐	No □ Yes □	+ Rectus ☐ + Psoas ☐		☐	
ASLR	L	N ☐ Y☐	NA☐ S☐ O☐	Pelvis/Trunk □ Hip □	BJL □ BMT □AMT□	□	Y □ N□ Worst side? R or L
	R	N ☐ Y☐	NA☐ S☐ O☐	Pelvis/Trunk □ Hip □	BJL □ BMT □AMT□	□	
ASLR core	L	N ☐ Y☐		Better □ Same □		☐	Y □ N□ Worst side? R or L
	R	N ☐ Y☐		Better □ Same □		☐	
	Comments:						

Bridge Series

Test		Pain	Deviation	Where	NT	Symmetry
Bridge		N ☐ Y☐	NA☐ S☐ O☐	Pelvis/Trunk □ Hip □	☐	
Bridge-LE EXT	L	N ☐ Y☐	NA☐ S☐ O☐	Pelvis/Trunk □ Hip □	☐	
Comments:						
Bridge-LE EXT-R	L	N ☐ Y☐	NA☐ S☐ O☐	Pelvis/Trunk □ Hip □	☐	
Comments:						

Bridge-LE EXT	R	N ☐ Y☐	NA☐ S☐ O☐	Pelvis/Trunk □ Hip □	☐	Y □ N□ Worst side? R or L
Comments:						
Bridge-LE EXT-R	R	N ☐ Y☐	NA☐ S☐ O☐	Pelvis/Trunk □ Hip □	☐	Y □ N□ Worst side? R or L
Comments:						

Prone/Quadruped Series

Test		Pain	Deviation	Where	NT	Symmetry
Hip EXT	L	N ☐ Y☐	NA☐ S☐ O☐	Pelvis/Trunk □ Hip □	☐	
Comments:						
Hip EX - UE Lift		N ☐ Y☐	NA☐ S☐ O☐	Pelvis/Trunk □ Sho □ Hip □	☐	
Comments:						
Hip EXT	R	N ☐ Y☐	NA☐ S☐ O☐	Pelvis/Trunk □ Hip □	☐	Y □ N□ Worst side? R or L
Comments:						
Hip EX - UE Lift		N ☐ Y☐	NA☐ S☐ O☐	Pelvis/Trunk □ Sho □ Hip □	☐	Y □ N□ Worst side? R or L
Comments:						

Legacy Fund Clinical Core

Date:
Subject #
TT **RT**

Flex Clearing		N ☐ Y☐	Hypo ☐Hyper ☐	Hip □ Thoracic □ Lumbar □	☐	
Comments:						
Rot Stab - Diagonal	L	N ☐ Y☐	NA☐ S☐ O☐	Pelvis/Trunk □ Sho □ Hip □	☐	
Comments:						
Rot Stab – Unilateral	L	N ☐ Y☐	NA☐ S☐ O☐	Pelvis/Trunk □ Sho □ Hip □	☐	
Comments: Unable ☐						
Rot Stab Diagonal	R	N ☐ Y☐	NA☐ S☐ O☐	Pelvis/Trunk □ Sho □ Hip □	☐	Y □ N□ Worst side? R or L
Comments:						
Rot Stab Unilat	R	N ☐ Y☐	NA☐ S☐ O☐	Pelvis/Trunk □ Sho □ Hip □	☐	Y □ N□ Worst side? R or L
Comments: Unable ☐						
EXT Clearing		N ☐ Y☐	Hypo☐ Hyper☐	Thoracic □ Lumbar □		
Comments:						
Push-Up		N ☐ Y☐	NA☐ S☐ O☐	Pelvis/trunk☐ Sho□	☐	Re-aligned Hands☐
Comments: Unable☐						

Standing Series

Test		Pain	Deviation	Where	NT	Symmetry	
Squat		N ☐ Y☐	NA☐ S☐ O☐	P/T □ Sho□ knee□ Ank□	☐	No Board	
w/ Board		N ☐ Y☐	NA☐ S☐ O☐	P/T □ Sho□ knee□ Ank□	☐	Board used☐	
Comments:							
Hurdle **Tibial Height:** **________in**	L	N ☐ Y☐	NA☐ S☐ O☐	P/T □ Sho□ knee□ Ank□	☐	LOB☐ Contact □	Y □ N□ Worst side? R or L
	R	N ☐ Y☐	NA☐ S☐ O☐	P/T □ Sho□ knee□ Ank□	☐	LOB☐ Contact □	
Comments:							
Lunge **Tibial Height:** **________in**	L	N ☐ Y☐	NA☐ S☐ O☐	P/T □ Sho□ knee□ Ank□	☐	LOB □	Y □ N□ Worst side? R or L
	R	N ☐ Y☐	NA☐ S☐ O☐	P/T □ Sho□ knee□ Ank□	☐	LOB □	
Comments:							

Legacy Fund Clinical Core

Date:
Subject #
TT **RT**

Upper Extremity Series

Test		**Pain**	**Deviation**	**Where**	**NT**	**Symmetry**				
Shoulder Clearing	L	N ☐ Y☐			☐					
	R	N ☐ Y☐			☐					
Comments:										
Shoulder Mobility	L	N ☐ Y☐	Hand length: __________in.		☐	Distance: in.				Y □ N□ Worst side? R or L
	R	N ☐ Y☐	Hand length: __________in.		☐	Distance: in.				
Comments:										
GIRD	L	N ☐ Y☐			☐	ER:	ER:	IR:	IR:	GIRD ☐
	R	N ☐ Y☐			☐	ER:	ER:	IR:	IR:	GIRD ☐
Comments:										
Scapular Dyskinesis	FLX	N☐ Y☐	NA☐ S☐ O☐	L ☐	☐	W ☐ D ☐	Comments:			
			NA☐ S☐ O☐	R ☐		W ☐ D ☐				
	ABD	N☐ Y☐	NA☐ S☐ O☐	L ☐	☐	W ☐ D ☐	Comments:			
			NA☐ S☐ O☐	R ☐		W ☐ D ☐				
Comments:										

CKCUEST

Trial 1:______________________ **Trial 2:**______________________

Dynamic Series

Test		**Pain**	**Deviation**	**Where**	**NT**	**Symmetry**	
Step Down	L	N ☐ Y☐	NA☐ S☐ O☐	P/T □ Sho□ knee□ Ank□	☐	Y □ N□ Worst side? R or L	
	R	N ☐ Y☐	NA☐ S☐ O☐	P/T □ Sho□ knee□ Ank□	☐		
Comments:							
SL Hop Dist	L	N ☐ Y☐	NA☐ S☐ O☐	Pelvis/Trunk □ Knee □	☐	T1: in. T2: in.	Y □ N□ Worst side? R or L
	R	N ☐ Y☐	NA☐ S☐ O☐	Pelvis/Trunk □ Knee □	☐	T1: in. T2: in.	
Comments:							

UHBE

Left T1:___________s Right T1:_________s

Left T2:___________s Right T2:_________s

LT3 (if needed):________s R3 (if needed):___________s

Core Control Clinical

Trial 1:_____________s 75cm ball (grey) ☐

Trial2:______________s 65cm ball (green) ☐

Trial 3 (if needed)_______s

Legacy Fund Clinical Core

Date:
Subject #
TT **RT**

Muscle Performance Tests

Test		Pain	Amount	Where	NT	Comments
Flexor Test		N ☐ Y☐			☐	Time: ___________s Shoulder pain: /10
Extensor Test		N ☐ Y☐			☐	Time: ___________s Shoulder pain: /10
DSSLT		N ☐ Y☐			☐	Hip flex angle: ___________ Shoulder pain: /10

Borg *During* Clinical Testing: ___________

Borg *After* Clinical Testing: ____________

Appendix 4.

Table 7. MSST detailed schema

TEST	TYPE	STATIC/ DYN	REGION
Modified Thomas test (MTT)	FLEX	STATIC	LE
Active straight leg raise (ASLR)	FLEX	STATIC	LE
Flexion clearing test (FLEX)	FLEX	STATIC	Trunk/Pelvis
Extension clearing test (EXT)	FLEX	STATIC	Trunk/Pelvis
Shoulder clearing test (SHO CLR)	FLEX	STATIC	UE
Shoulder mobility (SHO MOB)	FLEX	STATIC	UE
Glenohumeral internal rotation deficit (GIRD)	FLEX	STATIC	UE
Extensor endurance (TEE)	MP	STATIC	Trunk/Pelvis
Flexor endurance (FE)	MP	STATIC	Trunk/Pelvis
Active hip abduction (AHA)	MP	STATIC	LE/Hip
Active hip abduction resisted (AHAR)	MP	STATIC	LE/Hip
Closed kinetic chain upper extremity test (CKCUEST)	NMC/MP	DYN	UE
Double-leg lowering test (DLLT)	NMC	STATIC	Trunk/Pelvis
Side bridge (SB)	NMC	STATIC	Trunk/Pelvis
Side bridge with hip abduction (SBA)	NMC	STATIC	Trunk/Pelvis
Side bridge with hip abduction resisted (SBAR)	NMC	STATIC	Trunk/Pelvis
Bilateral hip bridge (HB)	NMC	STATIC	Trunk/Pelvis
Unilateral hip bridge (UHB)	NMC	STATIC	Trunk/Pelvis
Unilateral hip bridge resisted (UHBR)	NMC	STATIC	Trunk/Pelvis
Unilateral hip bridge endurance (UHBE)	NMC/MP	STATIC	Trunk/Pelvis
Prone hip extension (HE)	NMC	STATIC	Trunk/Pelvis

Hip extension with contralateral arm lift (HEUE)	NMC	STATIC	Trunk/Pelvis
Rotary stability (RS)	NMC	STATIC	Trunk/Pelvis
Trunk stability push-up (PUSH)	NMC	DYN	Trunk/Pelvis
Squat (SQUAT)	NMC	DYN	Trunk/Pelvis/LE
Hurdle step (HURDLE)	NMC	DYN	Trunk/Pelvis/LE
In-line lunge (LUNGE)	NMC	DYN	Trunk/Pelvis/LE
Scapular dyskinesis (SCAP DYS)	NMC	DYN	UE
Step down (STEP)	NMC	DYN	PELVIS/LE
Y-Balance Anterior (YBT)	NMC	DYN	PELVIS/LE
Single-leg hop for distance (HOP)	NMC	DYN	PELVIS/LE
Core Control Clinical Test (CCCT)	NMC	DYN	Trunk/Pelvis

Appendix 5.

Description of Lab Based Tests of Seated Core Stability

Balance Chair Specifications:

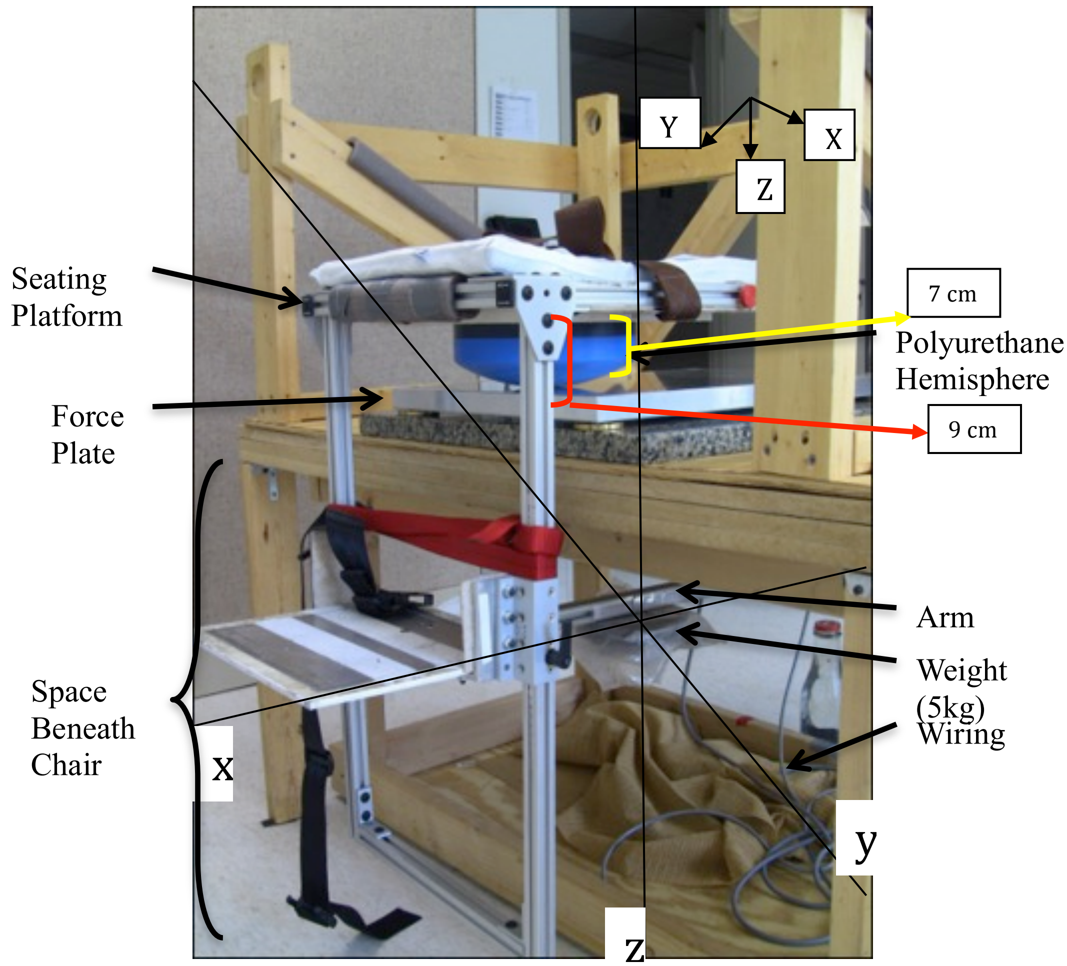


Figure 14: Balance Chair and Force Plate.

A seated balance platform and unstable seat is used for testing isolated trunk neuromuscular control (Figure 14). This seat is located on top of a multicomponent portable force plate (Kistler Inc) that tracks and provides real-time feedback of center of pressure data for our study protocols. A dedicated data collection computer with custom LabVIEW programs is used for all force data collection through a 32-channel A/D board. All data is collected at 2400 Hz.

The polyurethane hemisphere has a 44 cm diameter that allows approximately 15° of tilt of the chair in any direction without the chair frame hitting the force plate. The curved surface of hemisphere starts 7 cm below the seat surface with the pivot point located 9 cm under the seat. With addition of the sliding plate and the t-form (inside the white pillowcase) on top of it, the pivot point of the hemisphere is roughly 12 cm below the point of subject/ seat contact.

The location of the hemisphere along the y- direction can be changed, as a plate within the visible seat frame can slide front to back. The hemisphere location cannot be changed in the x-direction.

The specifications are as follows: the chair weighs approximately 20.5 kg; the seat width is 43.5 cm; the seat length is 60 cm; the leg rest side arms are 70 cm long; the footrest plate is 30 cm depth with a 32.5 cm width; the frame is built from T-slotted aluminum from 80/20—(http://www.8020.net/T-Slot-3.asp).

An adjustable counter-balance weight (5 kg) is located under the chair on an arm centered along the x-axis of the chair. This arm is attached to the bottom of the adjustable footrest. The weight serves to stabilize/ balance the chair and the location of the weight along the weight arm can be adjusted to match any position of the hemisphere.
The position of the counter-weight and the hemisphere are standardized according to the femur length of the subject. Thus the hemisphere is located roughly at the same point on each person and the counter-balance minimizes chair weight (thus the anterior tilt around x-axis of the chair given the weight of the leg rests). This reduces the need for the subject to counter the chair weight, reduces the activation level of the trunk muscles required to balance the seat and allows them to balance in a more neutral spine posture/ position. Starting from a more neutral position allows them to utilize their available lumbar/lower thoracic spine mobility during the tasks.

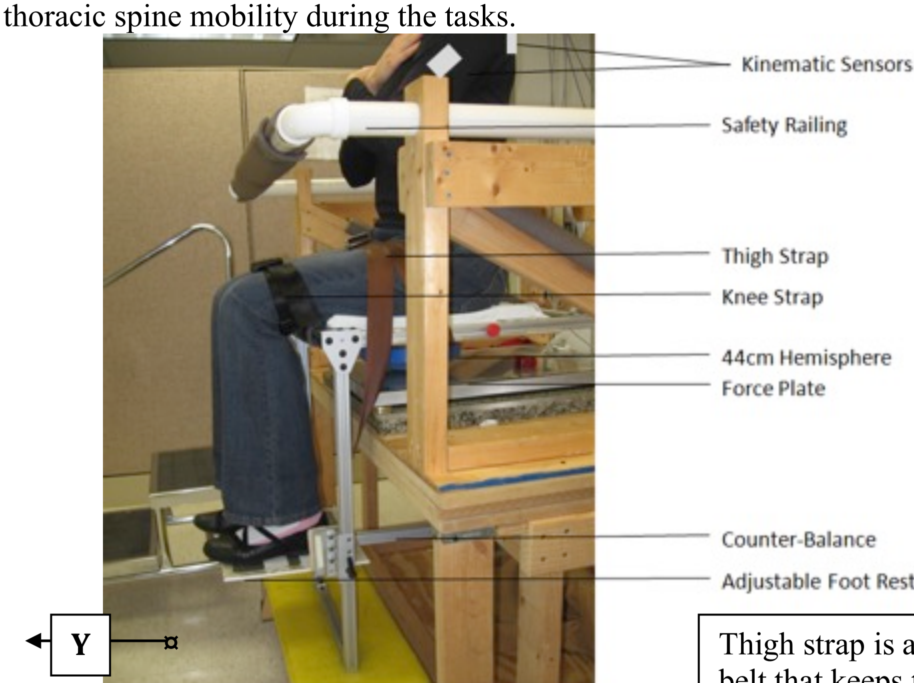


Figure 15: Set-up of subject on balance platform.

Thigh strap is a seat belt that keeps the thighs firmly positioned on the seat. The knee strap decreases the subject's ability to control the chair in the frontal plane (tilt around y-axis)

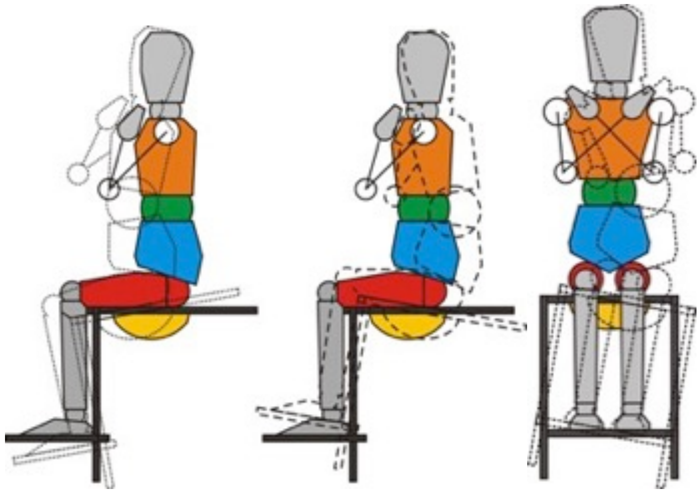


Figure 16: Schematic of a Subject

Proposed movements are coming from the pelvis, lumbar spine and lower thoracic levels.

The head should stay over the pelvis during the testing procedures (Figure 16).

Figure 17. Force Plate Control Unit

Instructions for the Seated Testing

Isolated core neuromuscular control is tested in the seated position to eliminate the role of the lower extremities. Using a fully adjustable seat and footrest, subjects will be placed in a standardized position of 90° of hip, knee and ankle flexion with the lumbar spine in a neutral position. By having each subject sit upright and cross their arms across their chest, we are able to localize movement to the lower thoracic, lumbar and pelvic regions. Force data are collected at 2400 Hz, filtered, down sampled (400 Hz) and COP time series are calculated. The control unit (Figure 9) for the force plate is set as follows: Fx, Fy is at 125 N, Fz at 500 N. The button at the bottom which read "Operate" zeroes the force plate.

Each subject will go though a standardized protocol to allow them to familiarize themselves with the chair apparatus.

To test static control, each subject will be instructed to maintain his or her balance with as little movement as possible. Following a practice trial, two 60 sec balance trials are completed with eyes open (EO) and closed (EC).

To test dynamic control, the subject has to maintain upright sitting balance and at the same time actively tilt the chair in multiple directions using the muscles of trunk and pelvis. To accomplish this, the subject receives real-time feedback of their center of pressure (COP) position as they move it toward different targets on a monitor that is directly in front of them. The subject is instructed to "move directly toward the target as quickly as possible and pause momentarily on the target". A standard period of time is allotted to activate the target resulting in a target color change that then signals the subject to move back to the center target with the same goal, activate it and move to another peripheral target. The target distance and location (0º, 45º, 90º, 135º, 180º, 225º, 270º, 315º) from the center of balance are standardized and the order does not change during the testing. The subject performs a practice trial, and then completes 3 trials.

Seated Balance Protocol

<u>Data Collection Set Up</u>

- Place subject on jig
    - Adjust seat so that subject is sitting in 90 degrees of hip flexion and 90 degrees of knee flexion.
    - Make sure subject is seated in middle of the chair and chair is centered on force plate (FP).
    - Align subjects ASISs with the middle of the ball.
    - Adjust ball position if necessary.
    - Record ball position.
    - Make sure chair leg is roughly 4 finger widths forward of the FP.
    - Allow subject to attempt to balance to assess the set up and subject positioning.
    - Adjust position of the feedback monitor for accommodate subject (if necessary).

<u>Zero FP and Calibrate Kinematics</u>

- Zero plate

  - o Ask subject to perform a dip using the wood rails
  - o Tilt the seat off the force plate
  - o Press "operating" button twice on box **(green light should be on)**
- Re-place seat and subject on plate, check the chair position on the FP and subject position on the chair
- Calibrate subject (neutral) in sitting. Instruction to subject to sit up straight with arms crossed across their chest. Save file under Seated folder; Name *subject#_seated:* ***003_seated***
- In scope mode, press run to make sure FP looks reasonable.

<u>Seated Balance Protocol (2 trials EO & EC)</u>

Open Labview Program: FP& EMGacq dev 8d.vi (Figure 18).

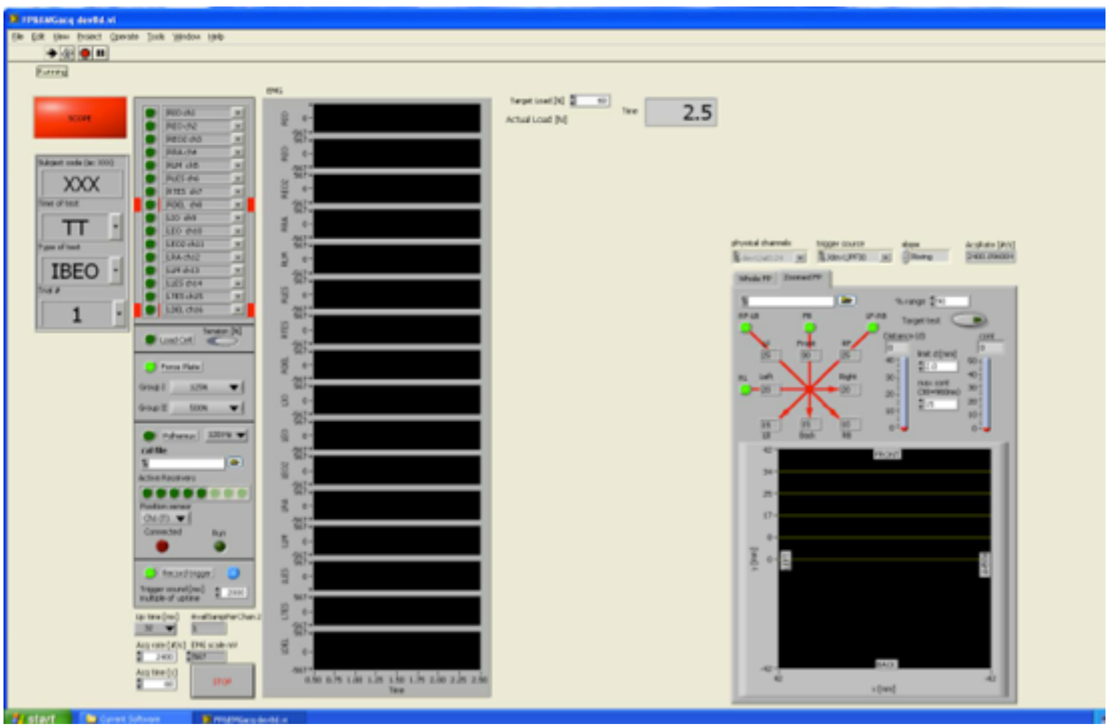


Figure 18: FP& EMGacq dev 8d.vi.

- **Set data collection time to 60 seconds, turn off trigger module and input "0" seconds.**
- Instruction provided to subjects prior to testing is standardized: **"Keep your arms crossed across your chest. While sitting up straight, balance the chair. The goal is stay as still as possible and not let the sides of the chair touch the force plate."** No further instruction is provided.
- Ask subject to place arms on railing in rested position between trials; if the subject appears to be fatiguing, also place foot rest on step stool.
- Have subject perform 1 -30 second practice trial with eyes open – if you leave the data collection on 'scope" you can monitor the read out of potential problems. *Make sure when subject is balancing that chair legs are 3 finger widths from front of platform.*

- Change mode on software to "Save Data":
    - Hit run and enter the appropriate file name
        - subject#_EO (or EC) + Trial # : e.g.: **002_EO3**
    - Have patient take hands off of railing and obtain balance.
    - Once balance obtained, press the trigger button.
- Record 2 consecutive trials of 60 seconds each with eyes open (EO) separated by a 30 second rest period between each trial.
- Allow a 30 second rest period.
- Provide 1 – 30 second practice trial with eyes closed (EC).
- Record 2 consecutive trials of 60 seconds each with eyes closed separated by a 30 second rest period between each trial.

<u>Dynamic Boundaries Test (2 trials)</u>

- Open the ***Target Limit. Vi*** **(Figure 19).** Explain the test is designed to measure how accurately and far they can tilt the chair in all directions.
- Settings 125N, 500N, .2 seconds, 2400 Hz, Limit of Tolerance to 0.1.
- Demonstrate the general concept of the target test to the subject.
- With the subject holding onto the railing, tilt the chair in all directions, while telling the subject which direction you are going (***no visual feedback***).
- With the subject holding onto the railing, have them tilt the chair as far as they can in all directions (***no visual feedback***).
- Instructions***: "With your arm across your chest balance the chair. On my cue, you should tilt the chair in the stated direction (forward, back…) staying as close to the line as possible but tilting as far as you can, without losing your balance."***
- Hit Run, have the subject balance at least 5 seconds so program can find center of pressure (CoP).. Then hit START.   The first direction dotted line pops up, tell the subject which direction they should move. Start with tilt forward, then back. Then hit NEXT DIRECTION. Then do tilt to LEFT… and continue until all movements have been completed. Hit NEXT DIRECTION again at end of data collection to post data to graphs.

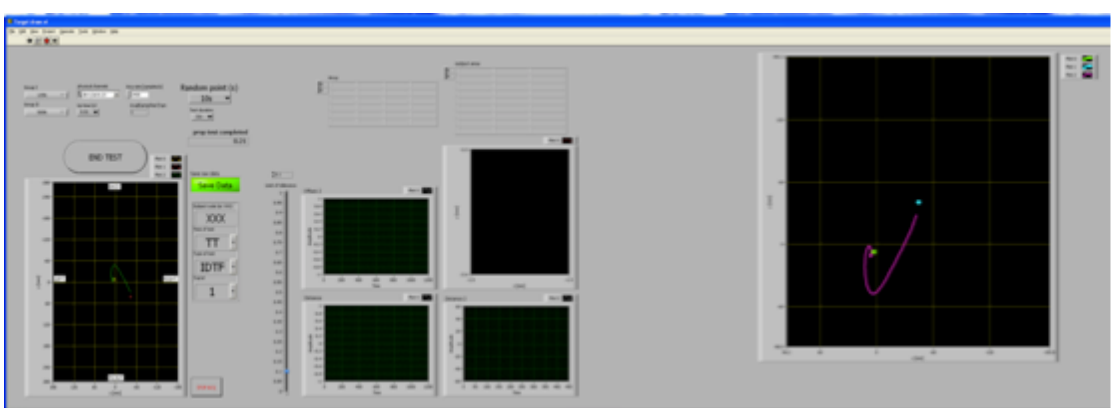


Figure 19: Target Limit.vi.

- <u>ORDER of MOVEMENT</u>:
  - Front -- back
  - Left -- right
  - Front right (*say* "towards top") – left back (*say* "towards the bottom")
  - Front left – right back.
- Then hit STOP PROCESSING (Figure 20).
- The first time trial is used as a practice trial.
- Turn ON the **Save Data** button.
- Restart the program and save the next 2 trials.
- You will be prompted at the beginning to enter the appropriate file name:
  - subject#__"db" + trial#
  - e.g.: **002_db2**
  - It will save two separate files under the file name provided. 1) **xxx.lfp** (limit target file) and 2) **xxx.tfp** (total data file)
- Record 2 trials of the subject, remember to have them finding their balance point, then hit start and have the subjects perform maximum tilt forward, back, right and left as per the program order.

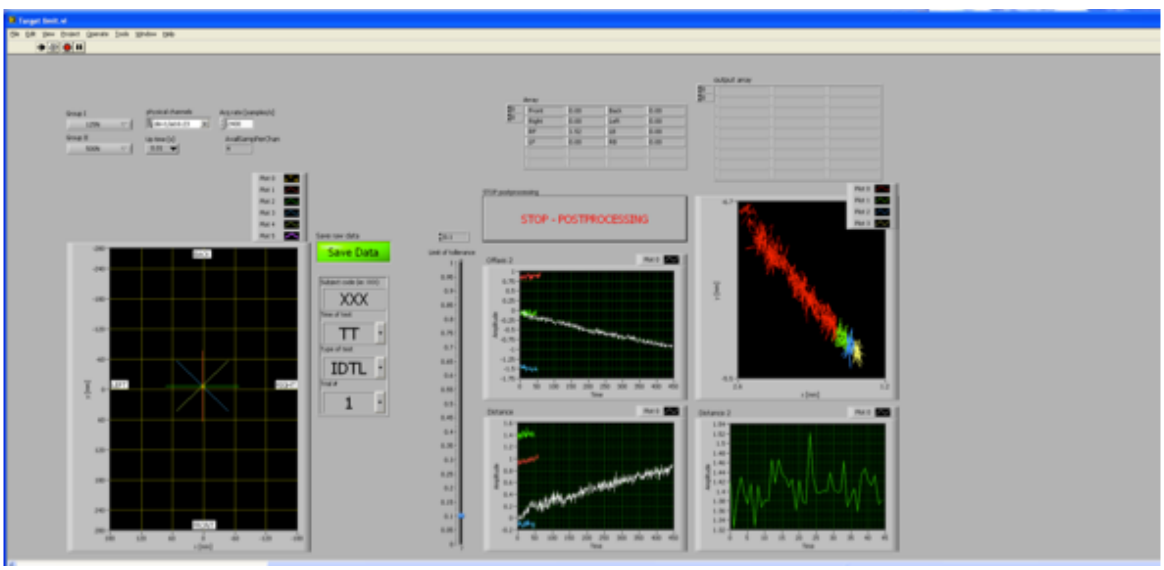


Figure 20: Target Limit.vi, after a trial has been completed.

<u>Seated Target Protocol (4 trials)</u>

- **Open Labview Program: FP& EMGacq dev 8d.vi**
- Turn Target Module ON
- Set parameters for targets F = 2; v = 0.2 (Figure 21).
- Set the target limits percentage at 70% for the first practice trial.
- Load the dynamic stability file **xxx.lfp** file.
- Set data collection to 30 seconds. Turn off trigger module, set to "0" seconds.
- Set on scope mode. FP module ON.
- Explain the purpose of the test.

- Instructions:
  "Keep your arms crossed across your chest. While sitting up straight, balance the chair. You will be tilting the chair (just like in the previous test) toward each target which are set along the lines from the previous program. You are to move as quickly and accurately as you can toward the solid GREEN target. Once the target color changes to RED, go back to the CENTER target. Look for next solid GREEN target to appear after you activate the center target and it turns RED.
- Ask subject to place hands on railing in rested position between trials.
- Have the subject practice on scope mode.
- <u>*Reset target limits to **90%***</u>. *Do not tell the subject you reset them*. Have them complete a second practice trial in scope mode.
- Change mode on software to "Save Data"
- Hit run and enter the appropriate file name
  - subject#_"**t**" + trial#
  - e.g**.: 002_t2**
- Have patient take hands off of railing and obtain balance. Once balance obtained press the trigger button and hit START on the TARGET TEST screen. There is no specific time set for this test; it will run until the subject completed the target test. Perform 3 trials.

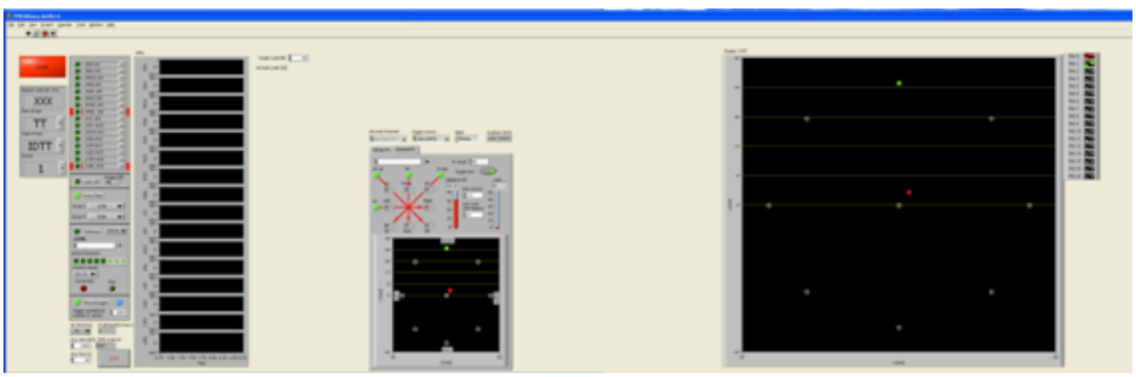


Figure 21: FP& EMGacq dev 8d.vi set for Target Test.

Appendix 6.

General Instructions

It is important that you *read the instructions to the subject as stated in this manual*. Lack of consistency in instructions and performance of the tests introduces considerable error and variability to the data. Given that data is being is collected by several individuals, this issue is important for securing quality data.

If the subject has difficulty correctly following instructions, it may be necessary to demonstrate and correct the start positions for each test. This is important to ensure quality tests and consistency across subjects.

The subject is allowed a maximum of 3 attempts for any given test. Do not give feedback about how they are to perform the movement. You are allowed to inform them if they have assumed the correct starting position and performed what you have requested.

Please perform each test series in the order presented here.

When applying resistance to a test position, *gradually* onset the force, and apply the force for at least 5 seconds. Observe for changes in control or limb position.

This manual includes figures of correct testing positions for each test. In some cases, figures of common faults are included. There is a video that accompanies this manual so that you may review the correct performance of these tests and practice rating the performance on example tests.

When completing the data collection sheet:

Please check all boxes within each section. You do not have to ask if there was pain after every test; however, you should ask the subject at the beginning of the testing session to let you know if they have pain with any of the individual tests. You may want to remind them of this periodically throughout the testing session.

Check "NONE" if there were no deviations from the correct performance of the movement.
Check "SUBTLE" if there were questionable or mild deviations.
Check "OBVI" if there were marked or clear deviations. If deviations were seen, indicate where the observed deviations occurred. Please include any comments that you feel are important for further qualifying any noted deviations.

If subtle or obvious deviations are occurring at 2 or regions, score the worst deviation and where it occurred. You can comment on other deviation in the comments section.

If the test was not performed, check the box for NT and comment on why it was not performed.

After completing tests that are performed bilaterally, please indicate if the results were symmetrical or asymmetrical by checking the appropriate box. If **asymmetrical**, then *circle* the letter of the **side of the poorest performance.**

For example, this finding indicates that the test was not symmetrical and that test performance on the right side was poorer than that on the left:

Y□ N □
® or L

SIDE-LYING SERIES

For ALL Side Lying Tests

The following are considered representative of poor control:

1. Hip does not remain in neutral rotation IR/ER occurs with movement
2. Pelvis does not remain in neutral, rotation occurs in sagittal, frontal (i.e. hip hike), or transverse plane
3. Cervical, thoracic, and lumbar spine do not remain neutral, rotation occurs in sagittal, frontal or transverse plane
4. Lack of symmetry in test performance between the left and right side
5. Any trunk movement prior to, during, or after active hip abduction

The following is considered hip weakness:

1. Active ABD motion less than full passive motion
- If hip weakness present, check the corresponding box.

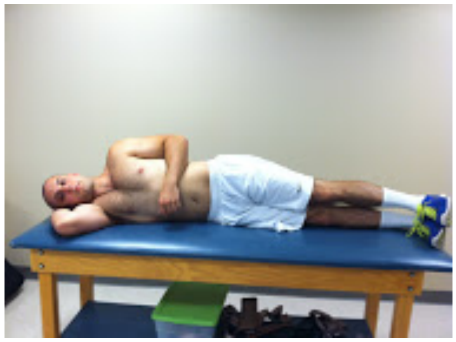
ACTIVE HIP ABDUCTION:

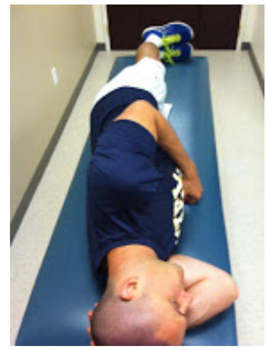
Instructions to the subject: *Lie on your side with your legs stacked on top of each other knees straight, toes pulled toward shins and pointing forward, and body in a straight line. Place your top hand on your stomach with arm along your side and your bottom arm under your head. Lift your top leg toward the ceiling as high as you can, maintaining your body position and top leg over bottom leg.*

Instructions to tester: Place one hand on top of the subject's iliac crest and observe for movement deviations. When the subject has reached their maximum active hip abduction, check to make sure they have moved through the full motion by assessing if additional passive hip abduction can be achieved. Repeat bilaterally.
(Nelson-Wong, Flynn, & Callaghan, 2009)

ACTIVE HIP ABDUCTION

Starting Position



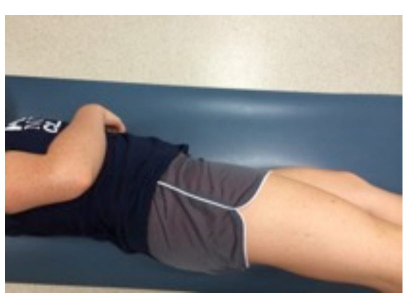


No Deviation

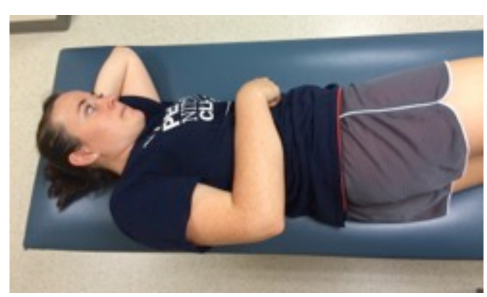
Hip Flexion

Hip External Rotation

Loss of Neutral Pelvis



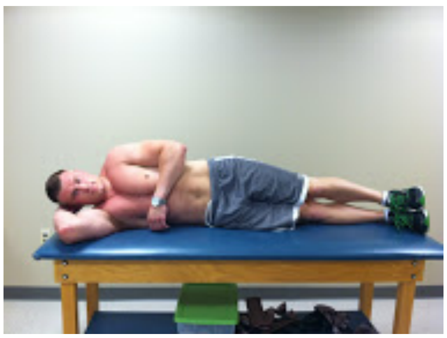
Loss of Neutral Spine



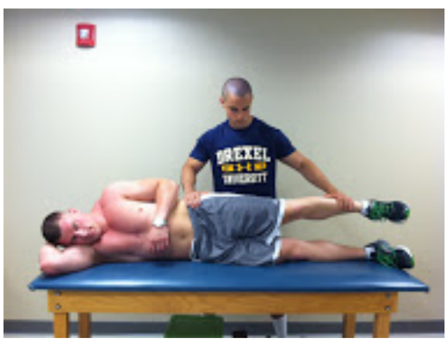
RESISTED ACTIVE HIP ABDUCTION

Instructions to subject: *This is the same test we just completed, but this time I want you to hold your top leg parallel to the ground as I try to push your leg toward the floor. Your job is to hold your top leg in place and not let me move you.*

Instructions to tester: Apply manual resistance proximal to lateral malleolus. Observe for movement deviation. Repeat bilaterally.



Starting Position



Testing Position

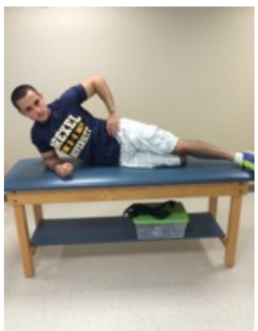
***All deviations are the same as noted in the Active Hip Abduction test**

SIDE BRIDGE

Instructions to subject: *Lie on your side propped up on your forearm with your shoulder over your elbow, and your bottom knee bent to 90 degrees. Your top and bottom thighs should be in line with one another and your top leg should be straight and your toes should be lifted towards your shin and be pointed forward. Lift your pelvis off the floor/table until your head, spine and bottom leg are in a straight line.*

Instructions to tester: Observe for ability to get into start position, aberrant movement and maintenance of pelvic height. Repeat bilaterally.
(Leetun, Ireland, Willson, Ballantyne, & Davis, 2004; Youdas, Guck, Hebrink, Rugotzke, Madson, & Hollman, 2008)

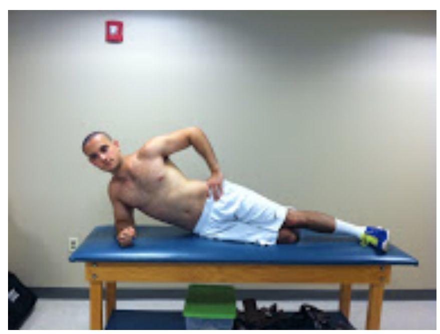
Start Position



No Deviation

Pelvic Rotation

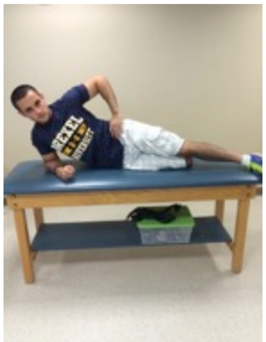
Inability to maintain position



SIDE BRIDGE WITH ACTIVE HIP ABDUCTION

Instructions to subject: *While maintaining the side bridge position, raise your top leg as high as you can and then bring it back to the starting position.*

Instructions to tester: Observe for ability to get into start position, top hip abduction height, movement deviations and maintenance of pelvic height during hip abduction. Repeat bilaterally.



Starting Position

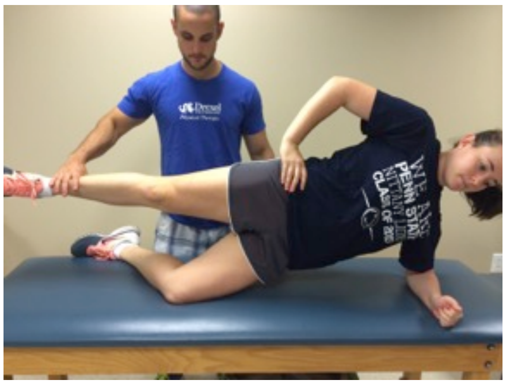
No Deviation

Inability to maintain bridge height

SIDE BRIDGE W/ ACTIVE HIP ABDUCTION & RESISTANCE

Instructions to subject: *Same position as the previous test, however, now I want you to hold your top leg parallel to the floor as I to try to push your top leg toward the floor. You should hold this position and do not allow me to push your leg down*.

Instructions to tester: Apply manual resistance proximal to lateral malleolus. Observe for ability to maintain position, aberrant movement and maintenance of pelvic height. Repeat bilaterally.



Testing Position

SUPINE SERIES

MODIFIED THOMAS TEST

The following are considered representative of tightness:

1. Thigh does not contact the table
2. Thigh contacts the table, but the knee does not achieve 80° flexion

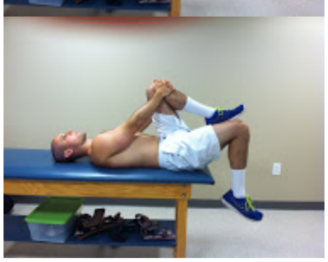
Instructions to subject: *Sit on the edge of the table and then lie back onto the table pulling both knees to your chest. Hold your left knee in this position while you lower the right leg toward the table.*

Instructions to tester: Place the subject in a position so that the lowered thigh is ½ way off the table when they are in their final position. Hold the knee in a position that keeps the low back/pelvis in neutral (with no excessive arching of back or putting the pelvis into a posterior tilt) when lowered thigh reaches end point. If lowered thigh does not make contact with table while low back/pelvis remains in neutral, tight Iliopsoas is indicated. If the knee joint angle is less than 80°, a tight rectus femoris is indicated. Repeat bilaterally.
(Harvey, 1998)

Starting Position

No Tightness

Tight Rectus Femoris



Tight Iliopsoas

ACTIVE STRAIGHT LEG RAISE (FMS)

The following are considered representative of poor control:
1. Non-moving leg does not remain stationary and in touch with the floor.
2. Head does not remain flat on floor.
3. Pelvis does not remain in neutral.
4. Trunk does not remain in neutral.
5. Lack of symmetrical performance on left and right

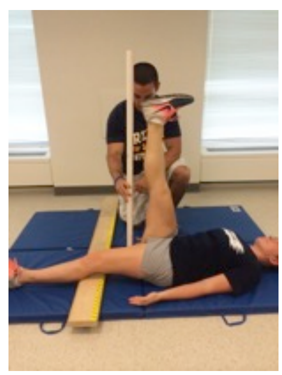
Instructions to subject: *Lie flat with the back of your knees against the board and your toes pointing up. Place both arms next to your body with the palms facing up. Pull the toes of your right foot toward your shin. With the right leg remaining straight and back of your left knee maintaining contact with the board, raise your right foot as high as possible.*

Instructions to tester: Both feet should be in neutral position with soles of the feet perpendicular to the floor. Find the midpoint between the ASIS and joint line of the knee; place the dowel at this position, perpendicular to the ground. The subject must maintain ankle dorsiflexion, knee extension, and neutral hips of both legs at end range. Observe for pelvis/trunk movement deviations. Once the subject has reached the end range, note the position of the upward ankle relative to the non-moving limb. If the malleolus does not pass the dowel, move the dowel to the position of the malleolus (similar to a plumb line) and note the position of the malleolus relative to the non-moving limb. If the subject is able to achieve a final position above the mid thigh, then there is no need to perform the next test (ASLR with Core Activation). Repeat bilaterally.
(Cook, Burton, & Hoogenboom, 2006a, 2006b)

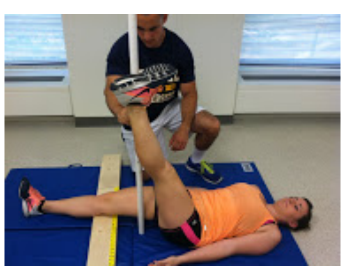
<u>ACTIVE STRAIGHT LEG RAISE:</u>

Starting Position

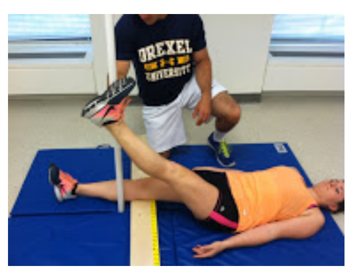
Above mid-thigh



Between joint line and mid thigh



Below knee joint line



HIP BRIDGE SERIES

The following are considered representative of poor control:

1. Inability to perform double-leg bridge to neutral hip position.
2. Loss of hip extension with knee extension.
3. Loss of neutral pelvis or spine during the task.
4. Amount of hip extension decreases with increased task difficulty.
6. Lack of symmetry between left and right side during knee extension task.

**For this series, the tests may flow as one test. The tester may have the subject perform the hip bridge and once in the final position, have the subject extend the knee, and then resist in the extended position.

HIP BRIDGE

Instructions to subject: *Lie on your back, knee bent to 90 degrees, feet hip width apart and arms across your chest. Lift your hips off the floor until your body is in a straight line.*

Instructions to tester: Observe for ability to achieve bridge position with neutral pelvis and spine.
(Okubo, Kaneoka, Imai, Shiina, Tatsumura, Izumi, & Miyakawa, 2010)

SINGLE LEG HIP BRIDGE W/ KNEE EXTENSION

*****The plant leg determines the side you are testing.***

Instructions to subject: *Same test as you just performed; however, now I want you to hold this position as you straighten your R/L knee while keeping your toes pulled toward your shins and your thighs parallel to one another.*

Instructions to tester: Observe for motion at hip, pelvis and spine. Repeat bilaterally.

SINGLE LEG HIP BRIDGE W/ KNEE EXTENSION RESISTED

*****The leg resisted determines the side you are testing.***

Instructions to subject: *Same test as you just performed; however, now I want you to hold your leg up, keeping your thighs parallel to one another, while I attempt to push your leg towards the floor.*

Instructions to tester: Apply manual resistance to leg proximal to ankle. Observe for motion at the hip, pelvis, and spine. Repeat bilaterally.

HIP BRIDGE SERIES:

HIP BRIDGE

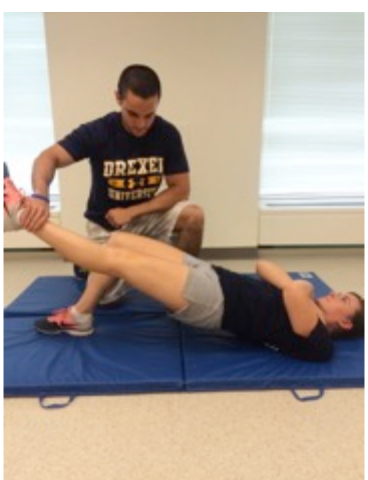
Starting Position | **Testing Position**

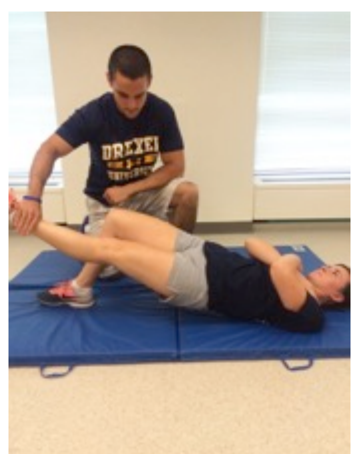
SINGLE LEG HIP BRIDGE WITH KNEE EXTENSION

No Deviation | **Loss of Neutral Pelvis**

SINGLE LEG HIP BRIDGE WITH KNEE EXTENSION RESISTED

No Deviation | **Loss of Neutral Pelvis**





PRONE & QUADRUPED SERIES

PRONE HIP EXTENSION (SINGLE LEG)

*****The leg lifted determines the side you are testing.***

The following are considered representative of poor control:

1. Inability to lift thigh off floor/table.
2. Hip IR/ER.
3. Loss of neutral pelvis or spine position.
4. Lack of symmetrical performance on left and right
5. Picking head up

Instructions to subject: *Lie on your stomach with your head face down on the table/floor with your hands under your forehead. Keeping your legs straight and toes pulled toward your shin, raise your left/right leg from the table until your thigh is just slightly off the table.*

Instructions to tester: Place a pillow under the stomach, if necessary, to achieve neutral spine/pelvis position. Observe leg height and motion at hip, pelvis and spine. Keep in mind that hip flexor tightness may affect ability to perform this movement. Repeat bilaterally.

PRONE HIP EXTENSION W/ CONTRALATERAL UPPER EXTREMITY LIFT

*****The leg lifted determines the side you are testing.***

The following are considered representative of poor control:

1. Inability to lift thigh off floor/table.
2. Hip IR/ER.
3. Loss of neutral pelvis or spine position.
4. Lack of symmetrical performance on left and right
5. Picking head up

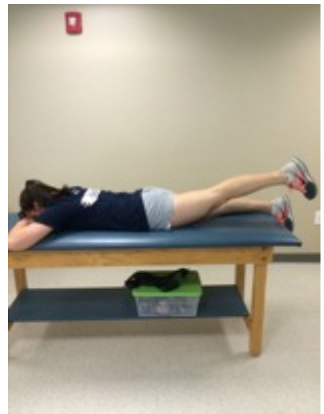
Instructions to subject: *Lie on your stomach, with your legs straight and toes pulled toward your shin. Place your left hand under your forehead and raise your right arm until it is just slightly off the table and then raise your left leg until your thigh is just slightly off the table.*

Instructions to tester: Observe arm and leg height and motion at hip, pelvis and spine. Place a pillow under the stomach, if necessary, to achieve neutral spine/pelvis position. Repeat bilaterally.

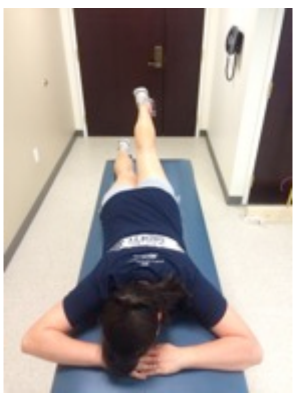
PRONE AND QUADRUPED SERIES:

Starting Position

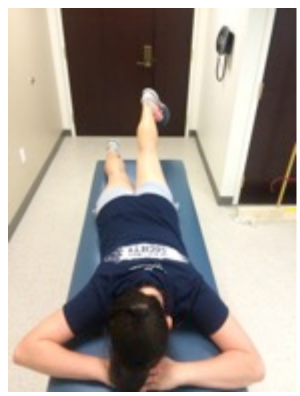
No Deviation



Loss of Neutral Pelvis

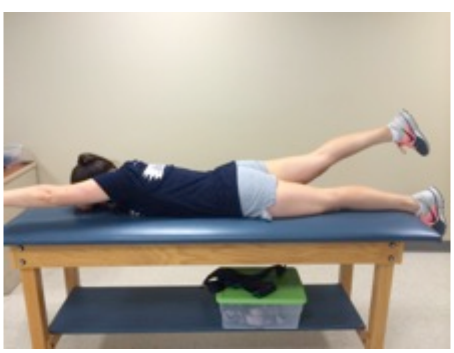


Hip External Rotation



PRONE HIP EXTENSION WITH CONTRALATERAL UE LIFT

No Deviation



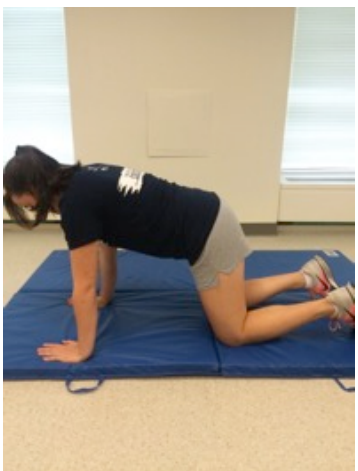
SPINAL FLEXION CLEARING TEST (FMS)
Assess the following:

1. Presence of pain with performance of the movement
2. Where the pain is located.
3. Excessive/limited motion of the hip or spine

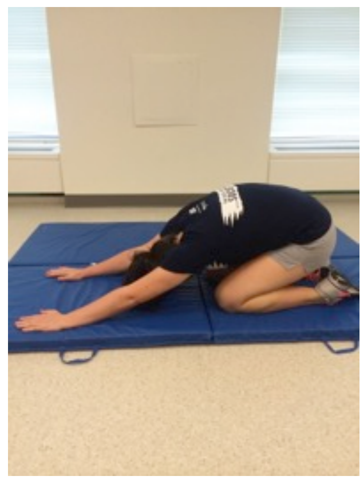
Instructions to subject: *Get on all fours, and rock your hips toward your heels. Lower your chest to your knees, and reach your hands in front of your body as far as possible. Do you feel any pain?*
(Cook et al., 2006a, 2006b)

Instructions to tester: Observe motion at the spine and hips. Make any comments you feel necessary about limited or excessive motion.

Starting Position



Final Position



ROTARY STABILITY (FMS)

***** The moving upper extremity indicates the side being scored.***

The following are considered representative of poor control:

1. Inability to perform ipsilateral testing position.
2. Lack of symmetrical performance between sides.
3. Inability to control trunk and pelvis during movement.

Instructions to subject:

For the Diagonal Pattern:

Get on your hands and knees over the board so that your hands are under your shoulders and your knees are under your hips. Your thumbs, knees, and toes must contact the sides of the board and your toes must be pulled towards your shins. Reach your right hand forward and your left leg backward at the same time until they just come off the floor about 6 inches. Then without touching down, touch your right elbow to your right knee directly over the board. Return to the extended position. Return to the start position.

For the Unilateral Pattern:

Reach your right hand forward and right leg backward at the same time, until they just come off the floor about 6 inches. Then without touching down, touch your right elbow to your right knee directly over the board. Return to the extended position. Return to the start position.

Instructions for tester: Have the subject get into a quadruped position with the board on the floor between the hand and knees. The board should be parallel to the spine, with the ankles in a neutral DF/PF position and the soles of the feet perpendicular to the floor. Hands should be flat on the floor, with the thumbs, knees, and feet all touching the board.

3 attempts may be performed for each testing position. Perform the diagonal pattern first. After completion of the diagonal pattern on each side, have the subject attempt the unilateral pattern.

Repeat bilaterally.

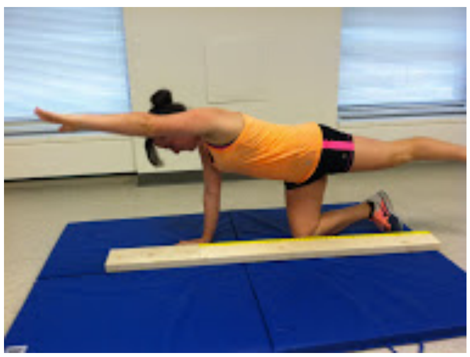
IF UNABLE to perform the diagonal movement, note this and move to the next test.

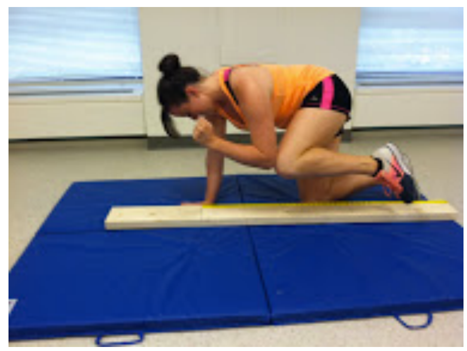
(Cook et al., 2006a, 2006b)

ROTARY STABILITY

Starting Position

Correct Unilateral Repetition





Correct Diagonal Repetition

SPINAL EXTENSION CLEARING TEST (FMS)
Assess the following:

1. Presence of pain with performance of the movement
2. Where the pain is located.
3. Excessive/limited motion of the spine/hips.

Instructions to subject: *While lying on your stomach, place your hands, palms down, under your shoulders. With no lower body movement, press your chest off the surface as much as possible by straightening your elbows. Do you feel any pain?*
(Cook et al., 2006a, 2006b)

Instructions to tester: Observe for position of pelvis. Pelvis should remain in contact with the floor at the end position. The thighs and pelvis in contact with the mat, the ASIS is slightly off the mat, and the elbows fully extended demonstrate a normal final test position. Excessive motion of the spine is demonstrated the ability to achieve full elbow extension with the ASIS in contact with the mat. Limited motion of the spine is demonstrated by full elbow extension with the pelvis and proximal thigh not in contact with the mat.

Start Position

Final Position

TRUNK STABILITY PUSH-UP (FMS)
The following are considered representative of poor control:

1. Body does not lift as a unit
2. Chest and stomach do not come off the floor simultaneously or remain in a neutral position throughout the movement.
3. Pain is present during any part of the movement. Note location.

Instructions to subject: *Lie face down with your arms extended overhead and your hands shoulder width apart. Pull your thumbs down in line with ____(forehead for men, chin for women). With your legs together, pull your toes toward your shins and lift your knees and elbows off the ground. While maintaining a rigid torso, push your body as one unit into a pushup position.*

Instructions to Tester: As many as 3 repetitions may be performed, but if the initial movement is performed as instructed, there is no need to perform further repetitions.

If the ***MALE*** subject is ***unable*** to perform the movement with the hands in line with the forehead, have the subject perform the movement again with the hands in line with the chin.

If the ***FEMALE*** subject is ***unable*** to perform the movement with the hands in line with the chin, have the subject perform the movement again with the hands in line with the clavicle.

(Cook et al., 2006a, 2006b)

Start Position

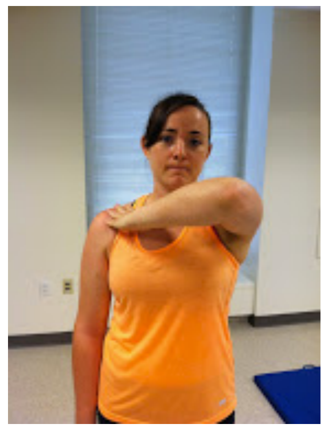
No Deviation

UPPER EXTREMITY SERIES

SHOULDER CLEARING TEST (FMS)
Assess the following:
1. Presence of pain with performance of the movement
2.Note where the pain is located.

Instructions to subject: *Stand tall with your feet together and arms hanging comfortably. Place your left palm on the front of your right shoulder. While maintaining palm placement, raise your left elbow as high as possible. Do you feel any pain? Repeat on the other side.*
(Cook et al., 2006a, 2006b)

Starting Position **Final Position**



SHOULDER MOBILITY (FMS)

Measurement:
****Top shoulder identifies the side being scored.***

1. Measure hand length.
2. Measure the distance between the two closest bony prominences on their hands once the final hand position is achieved.

Instructions to subject: *Stand tall with your feet together and arms hanging comfortably. Make a fist so your fingers are around your thumbs. In one motion, place the right fist overhead and down your back as far as possible while simultaneously taking your left fist up your back as far as possible. Do not "creep" your hands closer after their initial placement.*

Instructions to Tester: Measure hand length prior to testing. When measuring hand length, measure from the most distal wrist crease to the tip of the third digit. Measure the distance between the two closest bony prominences on their hands. Make sure the subject does not "walk" the hands toward each other following the initial placement. Perform 3 repetitions; record the distance of the closest reach. If the subject is able to touch their hands together with the initial movement, then record a distance of ZERO and move to the next side/test. Repeat bilaterally. Measure to the nearest 0.5-inch.

(Cook et al., 2006a, 2006b)

Measuring hand length

Final Position

SCAPULAR DYSKINESIS TEST

The following are considered representative of poor control:

1. Dysrhythmia
2. Winging

Operational Definitions

Normal scapulohumeral rhythm: The scapula is stable with minimal motion during the initial 30° to 60° of humerothoracic elevation, then smoothly and continuously rotates upward during elevation and smoothly and continuously rotates downward during humeral lowering. No evidence of winging is present.

Scapular dyskinesis: Either or both of the following motion abnormalities may be present.

Dysrhythmia: The scapula demonstrates premature or excessive elevation or protraction, nonsmooth or stuttering motion during arm elevation or lowering, or rapid downward rotation during arm lowering.

Winging: The medial border and/or inferior angle of the scapula are posteriorly displaced away from the posterior thorax.

Rating Scale
Each test movement (flexion and abduction) rated as

a) *Normal motion:* no evidence of abnormality
b) *Subtle abnormality:* mild or questionable evidence of abnormality, not consistently present
c) *Obvious abnormality:* striking, clearly apparent abnormality, evident on at least 3/5 trials (dysrhythmias or winging of 1 in (2.54 cm) or greater displacement of scapula from thorax)

Instructions to subject: *Stand in you natural, relaxed posture, keeping your elbows straight and thumbs pointing up, raise (for a 3-second count) and lower (for a 3-second count) your arms: A. straight in front of you and then B. Straight out to your side.*

Instructions to tester: The test consists of 5 repetitions of bilateral, active shoulder flexion and shoulder abduction. Each motion will be demonstrated, and subjects will be allowed to perform a few practice trials. Perform the movements with a 2lb (< 150 lbs) or 4lb (> 150 lbs) weight in each in hand.

(Kibler & McMullen, 2003)

<u>SCAPULAR DYSKINESIS TEST</u>

Scapular Winging

GLENOHUMERAL INTERNAL and EXTERNAL ROTATION PASSIVE ROM

Measurement:
1. Shoulder internal and external rotation in degrees.

Instructions to subject: *Lying on your back, bring your arm out to your side until your elbow is in line with your shoulder. Bend your elbow so your hand is pointed towards the ceiling and your palm is facing towards your feet. Relax, as I am going to rotate your arm backwards and forwards.*

Instructions to tester: PROM measures will be taken bilaterally. All measurements will be taken with the subject lying supine on a treatment table with their tested shoulder in 90 degrees of abduction, elbow flexed to 90 degrees, and the forearm in a neutral position (palm facing the subject's feet). The subject's arm (humerus) will be supported by the table and their elbow will be just off the table's edge. A towel roll may be placed under the distal humerus to ensure the arm is parallel to the table. The tester stands on the tested side of the subject with one hand (hand that is closest to the subject's head) over the anterior aspect of the subject's shoulder. This allows the examiner to <u>stabilize the scapula during the measurements</u> thereby isolating the motion to the glenohumeral joint.

The inclinometer is placed along the dorsal aspect of the midline of the subject's forearm. The end of the inclinometer nearest the wrist will be aligned with the distal most aspect of the ulnar head. The start position (zero degrees) for both internal and external rotation measures is as follows: shoulder in 90 degrees of abduction, elbow flexed to 90 degrees, forearm in neutral with the subject's hand/fingers pointing up towards the ceiling. From this position, the examiner will move the glenohumeral joint into external or internal rotation.

Internal rotation motion is stopped when the examiner feels resistance to the motion (firm end feel). Additionally, the examiner feels for forward movement of the subject's shoulder into the palm of their stabilizing hand. This procedure will be repeated a total of 2 times.

External rotation motion is stopped when the examiner feels resistance to the motion (firm end feel). Due to the fact that the posterior aspect of the shoulder is in contact with the table, posterior motion of the shoulder is restricted and less of a concern than anterior or forward motion during internal rotation. However, the examiner will also be assessing for any posterior movement of the subject's shoulder into their stabilizing hand so as to isolate motion to the glenohumeral joint. This procedure will be repeated a total of 2 times.

Repeat bilaterally.

(Wilk, Macrina, Fleisig, Porterfield, Simpson, Harker, Paparesta, & Andrews, 2011)

<u>GIRD</u>

Starting Position

Internal Rotation Testing Position

External Rotation Testing Position

STANDING SERIES

OVERHEAD SQUAT (FMS)

The following are considered representative of poor control:
1. Upper torso is not parallel with tibia OR aligned towards vertical
2. Femur does not go below horizontal.
3. Knees are not aligned over feet.
4. Dowel is not aligned over feet.
5. Any change in foot position.

Instructions to subject: *Stand tall with your feet approximately shoulder width apart and toes pointing forward. Grasp the dowel in both hands and place it horizontally on top of your head so your shoulders and elbows are at 90 degrees. Press the dowel up, so that it is directly above your head. Maintain an upright torso, and keep your feet flat on the ground and the dowel over your head, then squat down as far as possible. Hold the squat position for a count of one, and then return to the starting position.*

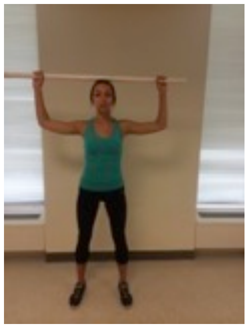
Instructions to Tester: Observe the subject from the front and the side. As many as 3 repetitions may be performed, but if the initial movement is performed as instructed, there is no need to perform further repetitions.

If the thighs do not go below horizontal, score their performance on the best 3 attempts. Then place the board under the subject's heels and have them repeat the movement. Alignment should remain unchanged even if the board is used to elevate the heels. Subjects are allowed 3 attempts without the board and then 3 attempts with the board, if needed. If board is used also, score the best performance with the board, if not indicated NT.

(Cook et al., 2006a, 2006b)

OVERHEAD SQUAT

Start Position



No Deviation

No Deviation – Board Used

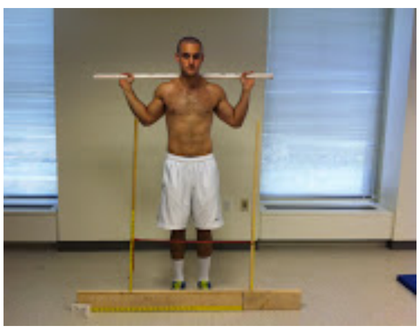
HURDLE STEP (FMS)
The leg stepping over the hurdle is the side being scored.

The following are considered representative of poor control:
1. Hips, knees and ankles do not remain aligned in the sagittal plane.
2. More than minimal movement is noted in lumbar spine or dowel.
3. Hurdle does not remain upright or the leg does not clear the tubing.

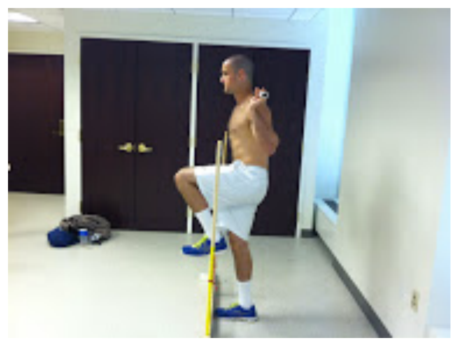
Instructions to subject: *Stand tall with your feet together and toes touching the board. Grasp the dowel with both hands and place it behind your neck and across your shoulders. While maintaining an upright posture, raise your right leg and step over the hurdle, making sure to raise your foot towards your shin and maintaining alignment of your ankle, knee and hip. Touch the floor with your heel and return to the starting position while maintaining alignment of your ankle, knee and hip*.

Instructions to Tester: Have the subject stand with the outside of the right foot against the base of the hurdle, in line with one of the uprights. Slide the tubing to the center of the tibial tuberosity, and adjust the other side until the tubing is level. Observe from the front and side. The performance is based on the leg stepping over the hurdle. Make sure the toes of the stance leg stay in contact with the board during and after each repetition. Repeat bilaterally.

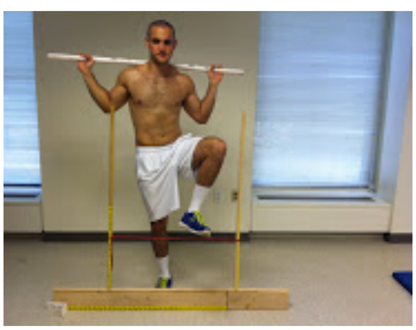
Starting Position



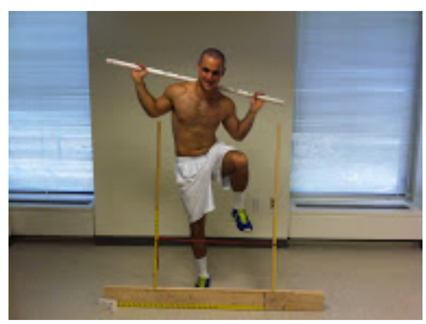
No Deviation



Hip Rotation



Trunk Flexion



(Cook et al., 2006a, 2006b)

In-Line Lunge

***The front leg identifies the side you are scoring.**

The following are considered representative of poor control:

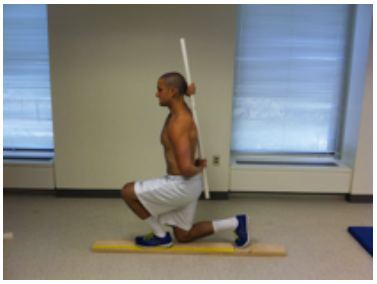
1. Dowel does not remain in contact with trunk
2. Trunk and dowel do not remain vertically aligned
3. Feet do not remain in sagittal plane
4. Knee does not touch board behind heel of front foot
5. Subject losses balance and falls off the board

Instructions to subject: *Place the dowel along your spine so it touches the back of your head, your upper back and the middle of your buttocks. While grasping the dowel, your right/left hand should be against the back of your neck, and the left/right hand should be against your lower back. Step onto the board with your right/left foot and your toe on the zero mark. The left/right heel should be placed at distance equal to tibial height. Both feet must be flat on the board with toes pointing forward. Maintain an upright posture so the dowel stays in contact with your head, upper back and top of your buttocks, then descend into a lunge position so your right knee touches the board behind your left/right heel. Return to the starting position*.

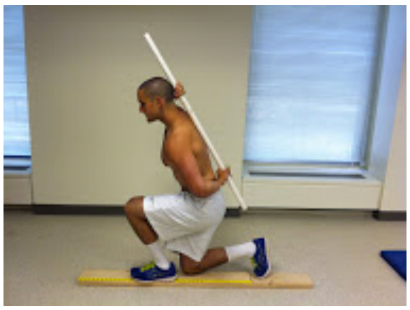
Instructions to Tester: Loss of balance during setup counts as 1 trial. Repeat bilaterally.

Starting Position

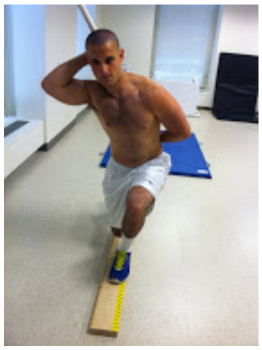
No Deviation



Trunk Flexion



Lateral Trunk Flexion



(Cook et al., 2006a, 2006b)

Step Down

The following are considered representative of poor control:

1. Pelvis does not remain in neutral.
2. Trunk does not remain in a neutral vertically aligned position
3. Knee collapses toward midline of the body
4. Stance heel lifts from the step
5. Lack of symmetrical performance between left and right
6. Motion is not performed smoothly
7. Balance is not maintained
8. Unable to achieve at least 60° knee flexion

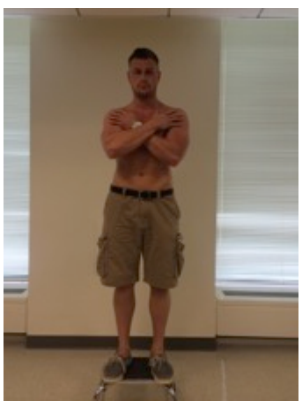
Instructions to the subject: *Stand on the stool, feet together, and cross your arms across your chest. Put your R/L foot in front of you and squat down towards the floor until your heel touches the floor and then return to the start position. Do this 5 times in a slow, controlled manner (approximately 1 squat every two seconds).*

Instructions to the Tester: Subjects are allowed up to 3 practice attempts. Repeat bilaterally.

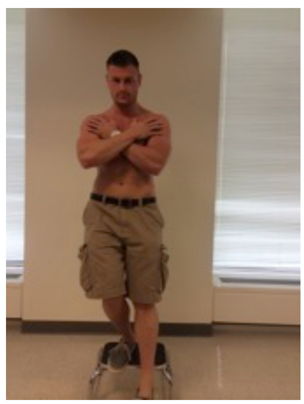
<u>Rating Scale</u>

a) *Normal motion:* no evidence of deviation
b) *Subtle deviation:* mild or questionable evidence of deviation, not consistently present
c) *Obvious deviation:* striking, clearly apparent deviation, evident on at least 3/5 trials

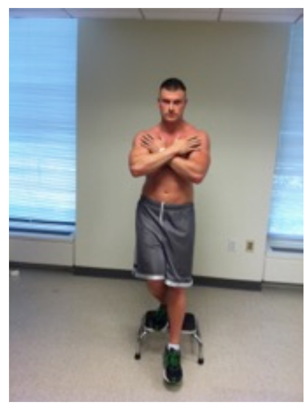
Starting Position



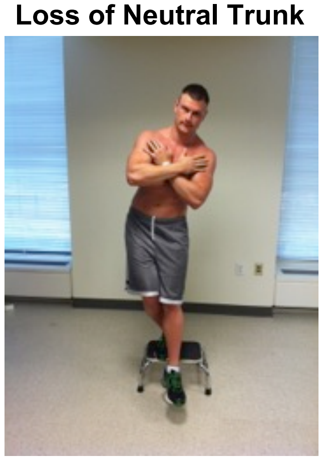
No Deviation



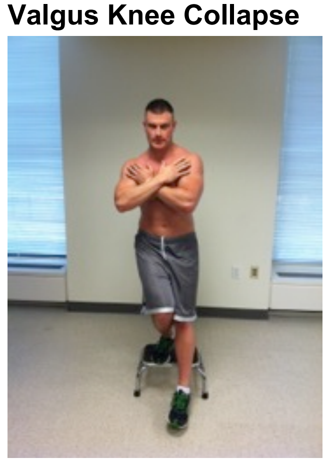
Loss of Neutral Pelvis



Loss of Neutral Trunk



Valgus Knee Collapse



SINGLE-LEG HOP FOR DISTANCE

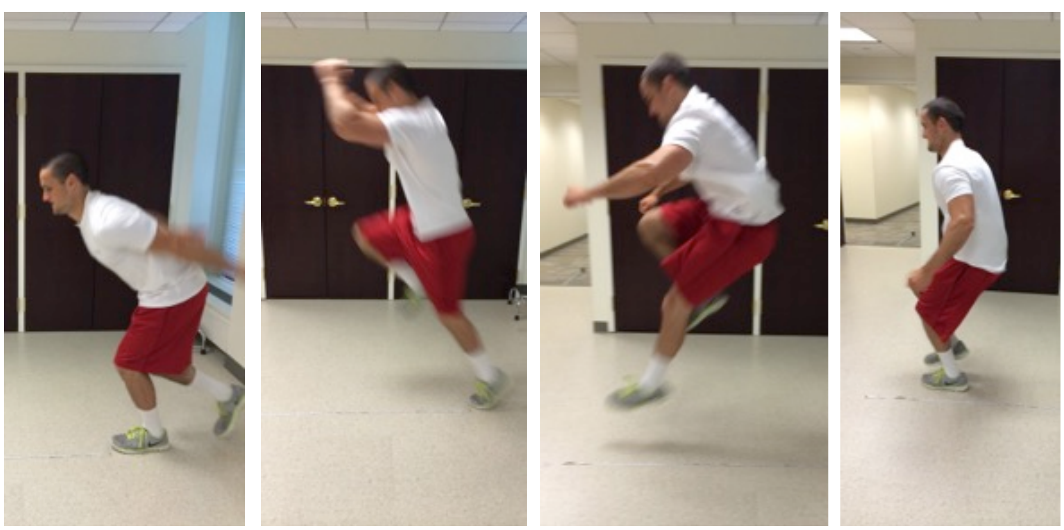
The following are considered representative of poor control:
1. Pelvis does not remain in neutral
2. Trunk does not remain in neutral, presence of excessive forward or side flexion
3. Knee collapses toward midline of the body
4. Lack of symmetry between left and right side

Instructions to subject: *Stand on one leg with your big toe behind the start line. When you are ready, jump forward as far as you can and land on the same foot that you jumped off of. Hold the landing for at least 2 seconds. Stay in that final position until the distance you have jumped is measured.*

Instructions to tester: For the hop test, the subjects perform one practice trial for each limb, followed by 2 measured and recorded trials. No restrictions are placed on arm movement during testing. To be deemed successful, the landing must be maintained for 2 seconds. Assess the hop from the front and observe for movement deviations. Once they have successfully completed the hop, have them stand in place and record the distance. Repeat bilaterally.

An unsuccessful hop is classified by any of the following:
1. Touching down of the contralateral lower extremity,
2. Touching down of either upper extremity,
3. Loss of balance, or
4. Additional hop on landing.

IF the hop was UNSUCCESSFUL, the subject should be reminded of what they were supposed to do, and the hop is repeated. No further instructions are provided to the subjects. Allow as many trials as needed until 2 successful hops are achieved. The distance hopped, measured from the start of the tape line to their heel, is recorded to the nearest half inch using a tape measure that is affixed to the floor.



(Brumitt, Heiderscheit, Manske, Niemuth, & Rauh, 2013)

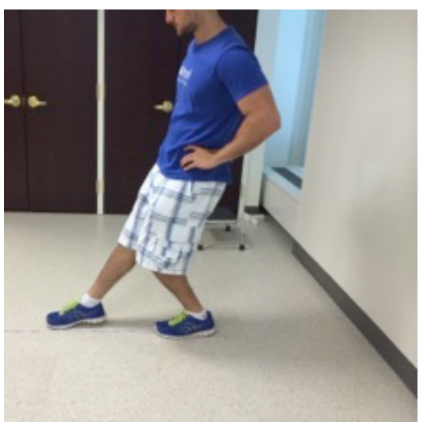
<u>**Y-BALANCE TEST ANTERIOR REACH**</u>

The following are considered representative of poor control:
1. Trunk does not remain in a neutral vertically aligned position.
2. Knee collapses toward midline of the body.
3. Stance heel lifts from the step.
4. Lack of symmetrical performance between sides

Instructions to subject: *Stand on one foot with your big toe at the beginning of the tape measure and your hands on your hips. While keeping your stance heel on the ground, reach the other foot out in front of you as far as you can, touch the tape, and then return your foot to the start position. Repeat 3 times.*

Instructions to Tester: This test is performed with the subject barefoot. Record the distance reached (cm) on each trial. The trial is considered unsuccessful if the hands come off the hips, the stance heel lifts from the ground, or the person loses balance. Allow as many trials as needed until 3 successful consecutive reaches are achieved. Comment on overall quality of the movement. Repeat bilaterally.

An unsuccessful reach is classified by any of the following:
1. Stance heel does not remain on the ground.
2. Hands do not remain on hips.
3. Reaching foot is used for balance/support.



Anterior Reach

(Plisky, Rauh, Kaminski, & Underwood, 2006)

MUSCLE CAPACITY TESTS

UNILATERAL HIP BRIDGE ENDURANCE (UHBE)

*****The leg in contact with the table is the side being tested.***

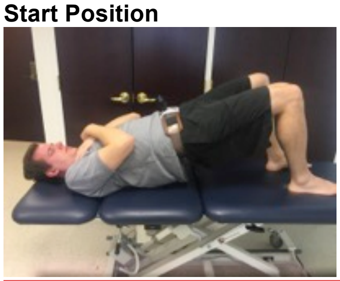
The following are considered representative of poor control:

1. Inability to perform double-leg bridge to neutral hip position.
2. Loss of hip extension with knee extension.
3. Loss of neutral pelvis or spine during the task.
4. Amount of hip extension decreases with increased task difficulty.
5. Lack of symmetry between left and right side during knee extension task.

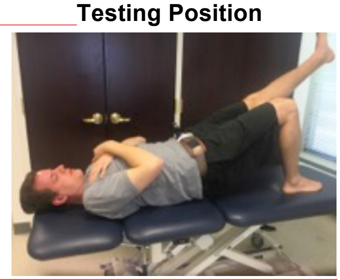
Instructions to subject: *Lie on your back, knee bent to 90 degrees, feet hip width apart and arms across your chest. Lift your hips off the floor until your body is in a straight line. Hold this position as you straighten your R/L knee while keeping your toes pulled toward your shins and your thighs parallel to one another. Try to maintain a neutral pelvis for as long as possible.*

Instructions to tester: Observe for ability to achieve bridge position with neutral pelvis and spine, motion at the hip, pelvis, and spine. The inclinometer belt should be tightly secured to the subject so that the belt is directly in contact with the ASIS bilaterally. Zero the inclinometer in the neutral double-leg bridge position and then instruct the subject to extend the knee. Start the timer once the knee is extended. The test is terminated once the subject achieves greater than or equal to a 10-degree change in pelvic position (in any plane of motion) or they choose to stop.
(Okubo et al., 2010)

Start Position



Testing Position



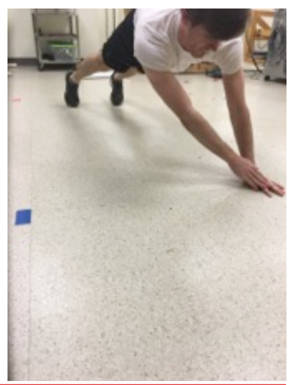
Closed Kinetic Chain Upper Extremity Stability Test (CKCUEST)

The following are considered representative of poor control:

1. Inability to achieve to neutral spine in start position.
2. Loss of neutral spine during task.
3. Loss of balance during the task.

Instructions to subject: Start in a standard push-up position, with one hand on each line of tape. Using your right hand, touch the tape under your left hand, and then return your right hand to the start position. Then use your left hand to touch the tape under your right hand, and then return your left hand to the start position. Each hand must touch the opposite line to count as a repetition. The score for this test based is the number of touches achieved in 15 seconds.

Instructions to tester: For this test, two lines of tape are placed 36 inches apart on the floor. Subjects start the test in a standard push-up position, with one hand on each line of tape. Each subject will be allowed to several practice trials to ensure proper form which is defined as: feet are shoulder width apart; shoulders, hips, knees and ankles are aligned in the coronal plane; each hand must touch the opposite line to count as a repetition. The score for this test based is the number of touches achieved in 15 seconds. The test is performed twice, and the numbers of touches are averaged across trials. Subjects will rest in between trials for one minute.
(Goldbeck & Davies, 2000).

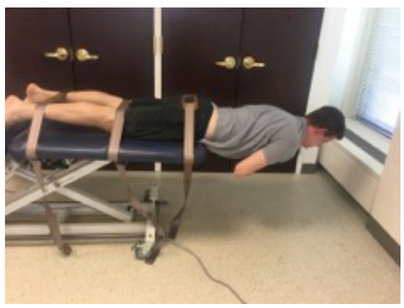
Start Position	Testing Position
	

TRUNK EXTENSOR ENDURANCE TEST
The following are considered representative of poor control:
1. Inability to assume the start position
2. Inability to maintain neutral spine during task

Instructions to subject: Lie on your stomach, with your hip bones at the edge of the table and your torso hanging from the edge of the table. Cross your arms across your chest and lift your chest so that your torso is parallel to the floor. Hold this position for as long as you can.

Instructions to tester: Use mobilization belts across the buttocks, posterior thigh above the knee, and at the ankles to secure the subject to the table. Use a standard goniometer to ensure that the test position is obtained (axis over greater trochanter, proximal arm bisecting the thigh, distal arm bisecting the trunk), and determine when the subject no longer can maintain the test position. Once the test position has been attained, start timing the test using a stopwatch. The test is terminated when the subject is no longer able to maintain their trunk in the test position as indicated by a 10 degree change in trunk alignment.
(McGill, 1999).

Testing Position

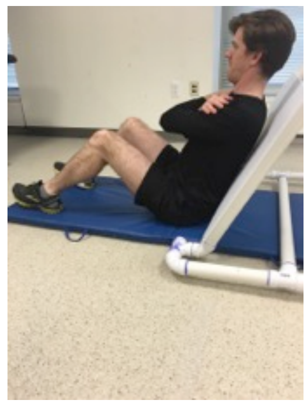


FLEXOR ENDURANCE TEST

Instructions to subject: Sit in a hooklying position (similar to the up position of a sit-up) with the wedge touching your back. Cross your hands across your chest and maintain this position for as long as possible.

Instructions to tester: Once the subject achieves the correct start position against the wedge, stand behind the subject, remove the wedge and start the timer using a stopwatch. The test is terminated when the subject changes their hip flexion angle by more than 10 degrees.
(McGill, 1999)

Testing Position

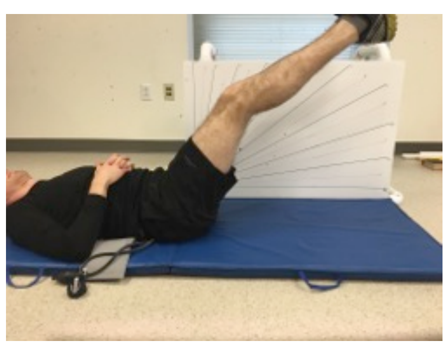


DOUBLE LEG LOWERING TEST

Instructions to subject: Lie on your back with your legs straight and lifted so that they are perpendicular to the ground. When I let go of your legs, slowly lower your legs towards the floor while maintaining your pelvic position.

Instructions to tester: Place the blood pressure cuff under the lumbar spine and inflate to 40 mmHg once the subject's hips are at 90 degrees of flexion and knees fully extended. Support the legs until it is time to begin the test. When the reading on the blood pressure cuff either: 1) exceeds 50 mmHg or, 2) goes below 30 mmHG, record the position of the hips (amount of hip flexion as recorded by a goniometer to the nearest 5 degrees).
(Lanning et al 2006)

Testing Position



CLINICAL CORE CONTROL TEST

Instructions to subject: For the warm up trial, sit up straight on the ball, feet on the ground, arms across your chest and move your pelvis side to side, front to back, and in a circular motion. For the practice trial: “Sit up straight, fold your arms across your chest, lift both feet off the ground and maintain your balance for as long as possible. Your heels and calves should remain in contact with the front of the ball at all times. You will be given a 30s practice trial if your feet touch the ground, the ball touches the wall or you fall into the wall or table just reset yourself and continue to practice. When I tell you to ‘GO’ you will lift your feet and begin.”

TEST TRIALS: “Sit up straight, fold your arms across your chest, lift both feet off the ground and maintain your balance for as long as possible. Your heels and calves should remain in contact with the front of the ball at all times. If your feet touch the ground, the ball touches the wall or you fall into the wall or table the trial will end. We are going to record 2- trials with 60s rest in between the trials. When I tell you to ‘GO’ you will lift your feet and begin.”

Instructions to tester: Give the subject 1-30s practice trial with both feet off the ground. Provide feedback if necessary. They may touch their feet to the ground as many times as they need to during the practice trial. The practice trial is meant as a familiarization trial as well as for the individual to figure out a successful balance strategy. Demonstrates a successful trial. A researcher should be sitting directly next to the subject to determine if the ball touches the wall and/or if the feet touch the ground. If subject loses their balance, their hands come off their chest, the ball touches the wall, or the feet touch the ground, the trial is over.
IF the 2 recorded trials are not within 15% CV of each other, a third trial will be performed. No more than 3 trials will be performed.

Testing Position

Appendix 7.

Table 8. Inter-rater reliability of MSST items: left and right kappas for athlete and dancer cohorts.

Test	Athlete k	Dancer k
L_AHA	0.30	0.26
R_AHA	0.62	0.26
L_AHAR	0.73	0.04
R_AHAR	0.48	0.08
L_SB	*No covariance	0.33
R_ SB	*No covariance	0.47
L_SBA	0.09	0.38
R_SBA	0.25	0.43
L_SBAR	0.57	0.65
R_SBAR	0.50	0.03
L_MTT	*No covariance	0.38
R_MTT	*No covariance	0.46
ASLR	*No covariance	*No covariance
HB	*No covariance	0.21
L HBE	0.36	0.06
R HBE	0.61	0.23
L HBER	*No covariance	*No covariance
R HBER	*No covariance	1.00
L_HIPEXT	0.75	0.86
R_HIPEXT	0.87	0.77
L_HIPEXTUE	0.03	0.1
R_HIPEXTUE	0.50	0.62
PUSH	*No covariance	0.81
RS	*No covariance	*No covariance
SQUAT		0.46
L_STEP	0.82	*No covariance
R_STEP	0.34	*No covariance
L_HUR	1.00	0.62
R_HUR	0.87	0.35
L_LUNGE	*No covariance	0.47
R_LUNGE	*No covariance	0.16

Appendix 8.

Data on Second Most Frequently Played Sport	Finding	Value

Sports Activity Questionnaire (SAQ)

Sports Activity Questionnaire

Relationship between Core Stability and Shoulder Injuries in Athletes

Please answer the following questions by writing your response in the blank spaces under the questions.

Data on Most Frequently Played Sport	Finding	Value
What sport do you play most frequently?	Low intensity	0.76
	Medium intensity	1.26
What position?	High intensity	1.76
Level: (varsity, JV, club, intramural, recreational, etc.)		
How many hours do you play a week? (competition, practice, and strength and conditioning) _________ (approx. hrs/week)	< 1 hour	0.5
	1-2 hours	1.5
Is this sport currently in season? Y N	2-3 hours	2.5
	3-4 hours	3.5
	> 4 hours (write in value)	4.5
How many months do you play in a year?	< 1 month	0.04
	1-3 months	0.17
	4-6 months	0.42
	7-9 months	0.67
	> 9 months	0.92

Describe strength and conditioning workouts (amount and type):

What sport do you play 2nd most frequently?	Low intensity	0.76
	Medium intensity	1.26
What position?	High intensity	1.76
Level: (varsity, JV, club, intramural, recreational, etc.)		
How many hours do you play a week? (competition, practice, and strength and conditioning)	< 1 hour	0.5
_________ (approx. hrs/ week)	1-2 hours	1.5
Is this sport currently in season? Y N	2-3 hours	2.5
	3-4 hours	3.5
	> 4 hours (write in value)	4.5
How many months do you play in a year?	< 1 month	0.04
	1-3 months	0.17
	4-6 months	0.42
	7-9 months	0.67
	> 9 months	0.92

Simple Sports Score: ___________

The sport intensity is divided into 3 levels: (1) low level (billiards sailing bowling golf etc) with an average energy expenditure of 0.76 MK/h; (2) middle level (badminton cycling dancing swimming tennis) with an average energy expenditure of 1.26 MJ/h; (3) high level (boxing basketball football rugby rowing) with an average energy expenditure of 1.76 MJ/h

Simple sports score = ((value for intensity of most frequent sport) * (value for weekly time of most frequent sport) * (value for yearly proportion of most frequent sport)) * ((value for intensity of second sport) * (value for weekly time of second sport) * (value for yearly proportion of second sport))
sport index = (SUM(points for all 4 parameters)) / 4

Classification of Sport

☐ Overhead ☐ Non-overhead shoulder ☐ Non-shoulder

Appendix 9.

Data collection forms and data reduction processes.

SET UP

Seated Thigh length (cm): ______
Record foot plate ______
Record position of ball ______
Record position of weight ______
Strap thighs together/ seat belt on
FP change (if any): Start from ______
Group I ______ *Group II* ______
(***Change on LabView program as well***)

Seated Template

FREE TARGT DRAW (4 trials)

- 1 CW, 1 CCW circle **O** (30s each)
- 1 figure **8** and 1 infinity ∞ sign (30s each)

File Names: XXX_YY_IDTF_Z

LIMITS OF STABILITY (2 trials)

- Tolerance limits (10% limit processing)

File Names: XXX_YY_IDTL_Z

SEATED BALANCE (2 trials Eyes OPEN) (60s)

- Trigger: 0, Acq time: 60

File Names: XXX_YY_IBEO_Z

SEATED BALANCE(2 trials Eyes CLOSED) (60s)

- Trigger: 0, Acq time: 60

File Names: XXX_YY_IBEC_Z

TARGET TEST (3 trials)

- Turn on target test
- Trigger: 1000, Acq time: N/A
- **1** practice trial (A) and **4** trials with 30sec rest in-between
- **90%**; limit d = **2**, max count = **15**

File Names: XXX_YY_IDTT_Z

Date:
Subject #

Notes:

Initials ____________ 1

Force Plate Post Processing (Piecewise, PWL)

1. Open LabView program name: BatchFP_PWL.vi (Figure 22).
Location: Z: \Research-GraduatePrograms\RehabSciencesProjects\Biomechanics\Sheri Silfies\New software(BackUP01222013)\PWL_FP

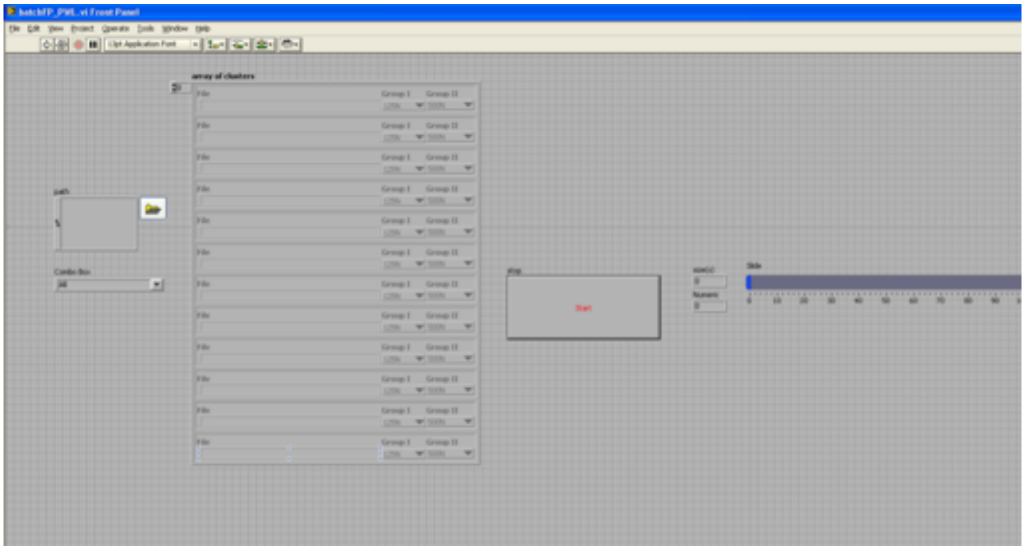


Figure 22: BatchFP_PWL.vi

2. Select folder:

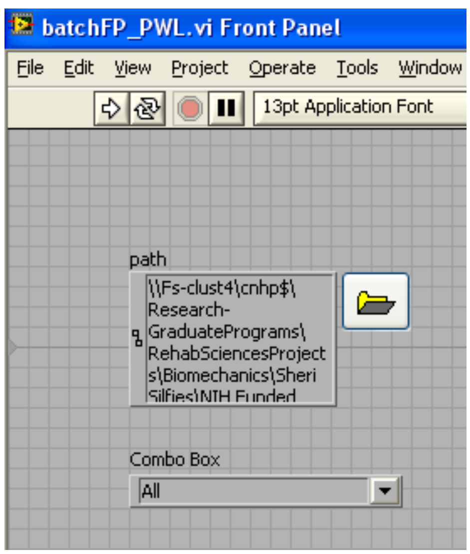


Figure 23: Selection of File for BatchFP_PWL.vi

Z: \Research-GraduatePrograms\RehabSciencesProjects\Biomechanics\Sheri Silfies\Marisa's Projects\Legacy Fund\Subjects\XXXX

3. Click arrow to run:

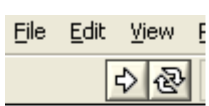


Figure 24: Run arrow for Labview programs.

4. Select Group I and Group II for each file based on value set during data collection (Default values: Group I: 125 N and Group II: 500 N; Figure 25).

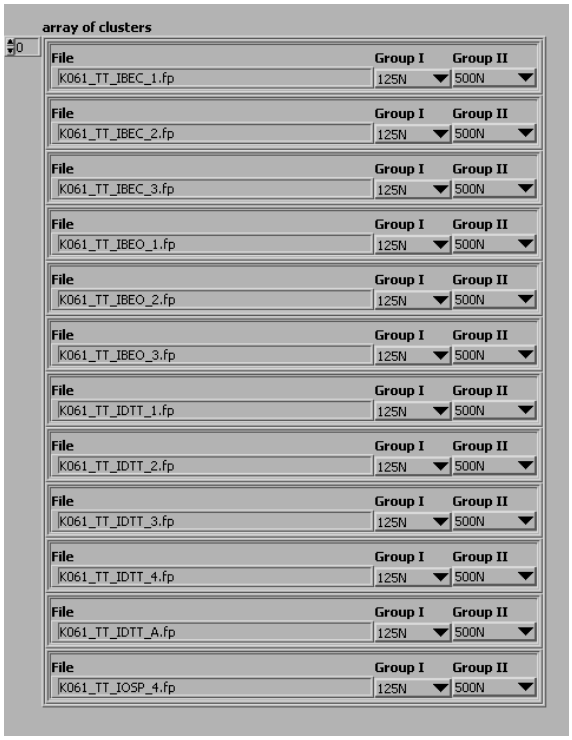


Figure 25: Selection of Force Parameters for BatchFP_PWL.vi

1. Click Start button .

The post-processing data will be saved in Z:\Research-GraduatePrograms\RehabSciencesProjects\Biomechanics\Sheri Silfies\Marisa's Projects\Legacy Fund\Subjects\XXXX\POSTP

File name: XXXX_TT_XXXX_X.pwl (subject number_TT_test_trial)

Force Plate IDTT test

1. Open LabView program name: Target_v3.vi (Figure 26).

Location: Z:\Research-GraduatePrograms\RehabSciencesProjects\Biomechanics\Sheri Silfies\Data Reduction Programs\LVpost\Target_v3 Folder\Target

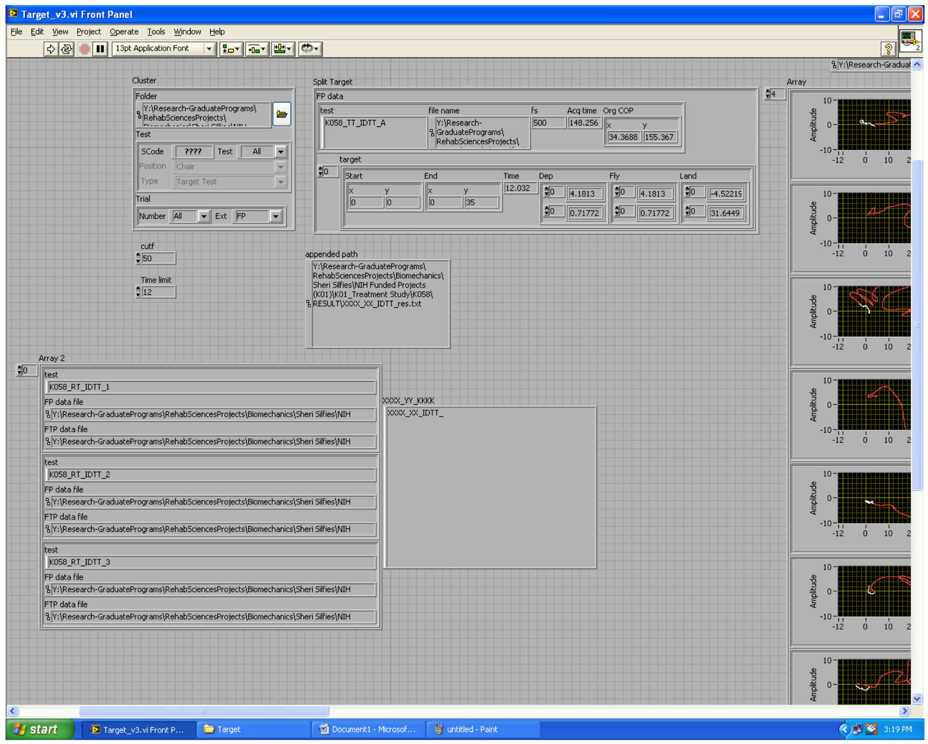


Figure 26: Target_v3.vi

2. Select folder (Figure 27)

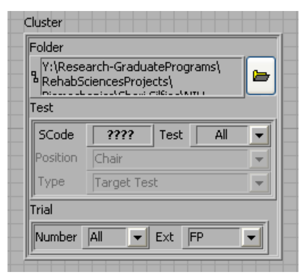


Figure 27: Selection of files for Target v3.vi

Y: \Research-GraduatePrograms\RehabSciencesProjects\Biomechanics\Sheri Silfies\Marisa's Projects\Legacy Fund\Subjects\XXXX

3. Click arrow to run.

The result will be saved in Z:\Research-GraduatePrograms\RehabSciencesProjects\ Biomechanics\Sheri Silfies\ Marisa's Projects\Legacy Fund\Subjects\XXXX\RESULT

File name: XXXX_XX_IDTT_res.txt

Rename the txt file as (subject #)_XX_IDTT_res.txt

*****subject number must be 4 characters***

4. Open Excel macro file name: **Target Macro TT Only 10.20.13.xlsm**
Location: Z:\Research-GraduatePrograms\RehabSciencesProjects\Biomechanics\Sheri Silfies\Marisa's Projects\Legacy Fund\Macros (Figure 28):

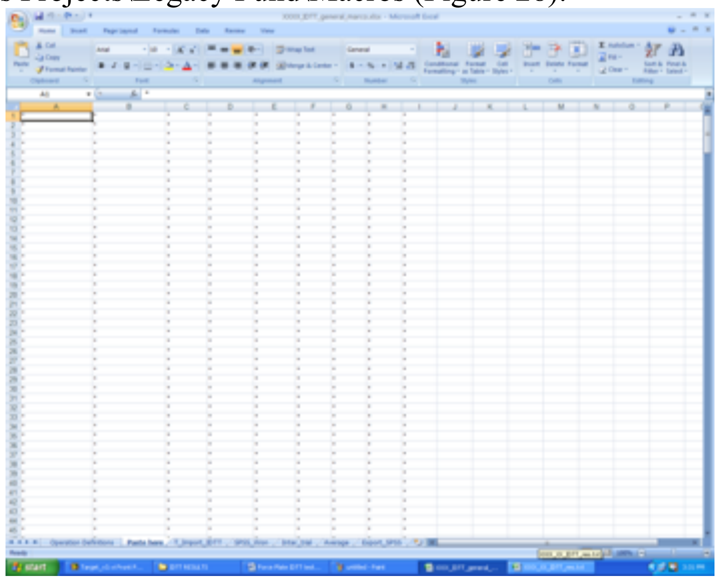


Figure 28. Target Macro.

5. Open result (XXXX_XX_IDTT_res.txt) in Excel, copy values, paste in macro (Figure 29):

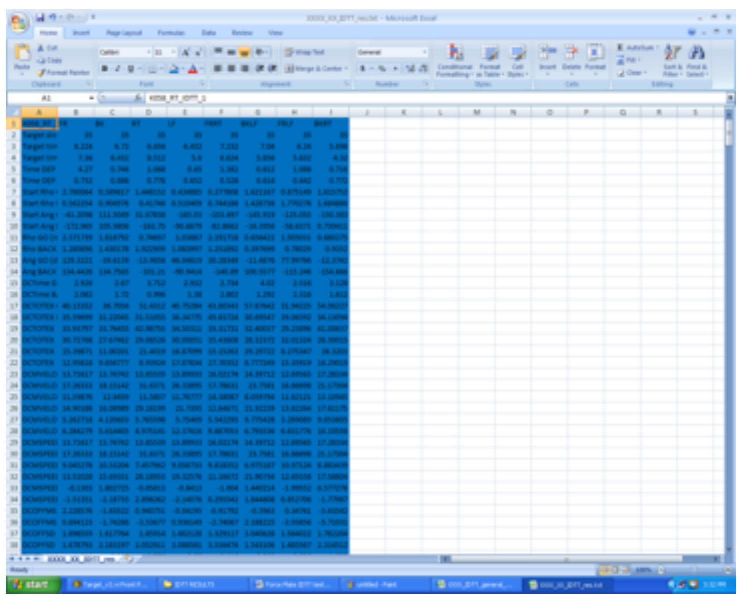


Figure 29: Target Macro with values.

6. Save file: XXXX_IDTT.xlsx
Z:\Research-GraduatePrograms\RehabSciencesProjects\Biomechanics\Sheri Silfies\Marisa's Projects\Legacy Fund\Subjects\Result

Force Plate IBEO and IBEC tests

1. Create Folder in each subject file labeled "RESULT"
2. Open LabView program name: batchEOEC.vi (Figure 30).

Location: Z: \Research-GraduatePrograms\RehabSciencesProjects\Biomechanics\Sheri Silfies\New software(BackUP01222013)\Target_v2

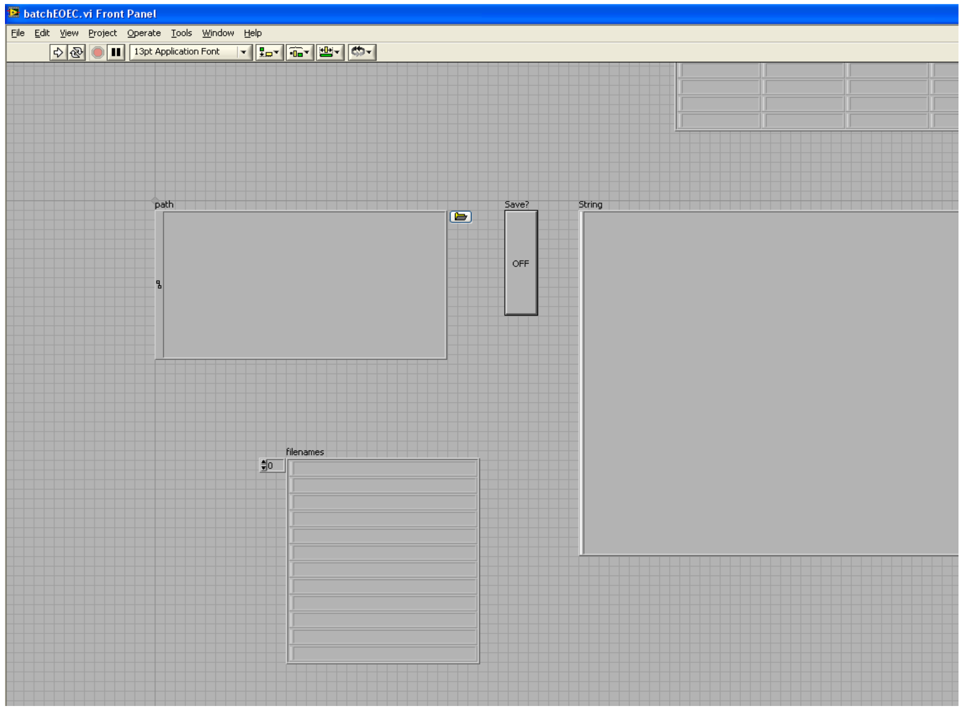


Figure 30: Batch EOEC.vi

3. Select folder and turn on "Save" (Figure 31).

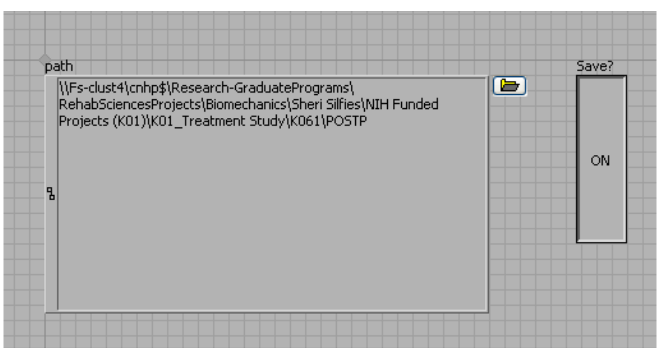


Figure 31: Selection of files for Batch EOEC.vi

Uses post-processed (.pwl) files
Z:\Research-GraduatePrograms\RehabSciencesProjects\Biomechanics\Sheri Silfies\Marisa's Projects\Legacy Fund\Subjects\XXXX\POSTP

4. Click arrow to run.
The result will be saved in Z:\Research-GraduatePrograms\RehabSciencesProjects \Biomechanics\Sheri Silfies\Marisa's Projects\Legacy Fund\Subjects\XXXX\RESULT
File name: XXXX_IBEOEC_result

5. Open Excel macro file name: **IBEOEC Macro TT Only 10.20.13** (Figure 32).

Location: Z:\Research-GraduatePrograms\RehabSciencesProjects\Biomechanics\Sheri Silfies\Marisa's Projects\Legacy Fund\Macros

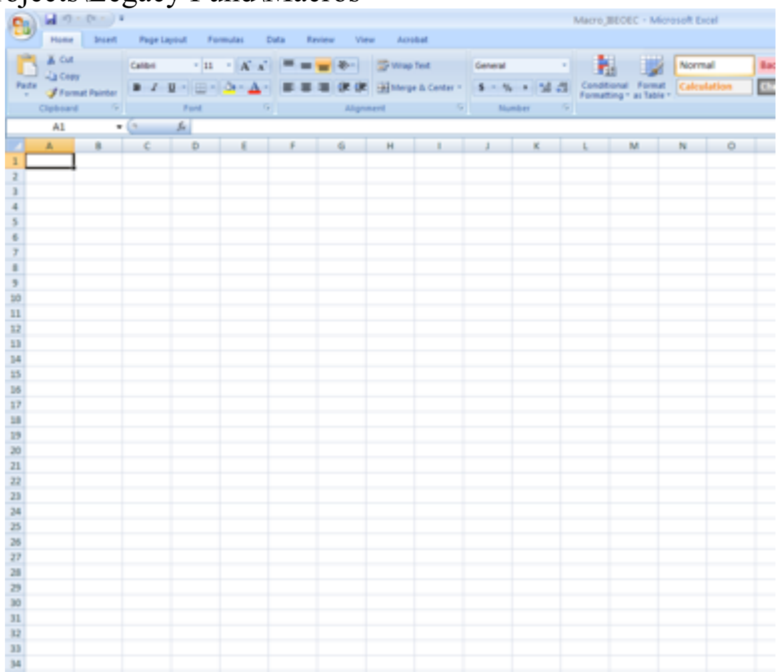
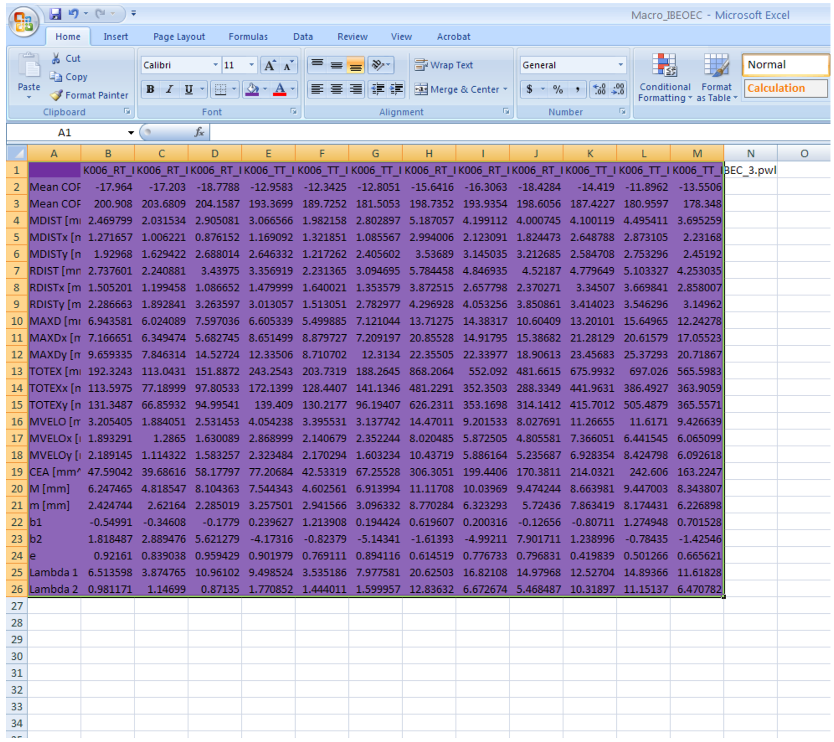


Figure 32: IBEOEC Macro.

6. Open result (XXXX_IBEOEC_result.txt) in Excel, copy values, paste in macro (Figure 33).



	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1		K006_RT_I	K006_RT_I	K006_RT_I	K006_TT_I	K006_TT_I	K006_TT_I	K006_RT_I	K006_RT_I	K006_RT_I	K006_TT_I	K006_TT_I	K006_TT_I	BEC_3.pwl
2	Mean COF	-17.964	-17.203	-18.7788	-12.9583	-12.3425	-12.8051	-15.6416	-16.3063	-18.4284	-14.419	-11.8962	-13.5506	
3	Mean COF	200.908	203.6809	204.1587	193.3699	189.7252	181.5053	198.7352	193.9354	198.6056	187.4227	180.9597	178.348	
4	MDIST [mi	2.469799	2.031534	2.905081	3.066566	1.982158	2.802897	5.187057	4.199112	4.000745	4.100119	4.495411	3.695259	
5	MDISTx [n	1.271657	1.006221	0.876152	1.169092	1.321851	1.085567	2.994006	2.123091	1.824473	2.648788	2.873105	2.23168	
6	MDISTy [n	1.92968	1.629422	2.688014	2.646332	1.217262	2.405602	3.53689	3.145035	3.212685	2.584708	2.753296	2.45192	
7	RDIST [mn	2.737601	2.240881	3.43975	3.356919	2.231365	3.094695	5.784458	4.846935	4.52187	4.779649	5.103327	4.253035	
8	RDISTx [m	1.505201	1.199458	1.086652	1.479999	1.640021	1.353579	3.872515	2.657798	2.370271	3.34507	3.669841	2.858007	
9	RDISTy [m	2.286663	1.892841	3.263597	3.013057	1.513051	2.782977	4.296928	4.053256	3.850861	3.414023	3.546296	3.14962	
10	MAXD [mi	6.943581	6.024089	7.597036	6.605339	5.499885	7.121044	13.71275	14.38317	10.60409	13.20101	15.64965	12.24278	
11	MAXDx [n	7.166651	6.349474	5.682745	8.651499	8.879727	7.209197	20.85528	14.91795	15.38682	21.28129	20.61579	17.05523	
12	MAXDy [n	9.659335	7.846314	14.52724	12.33506	8.710702	12.3134	22.35505	22.33977	18.90613	23.45683	25.37293	20.71867	
13	TOTEX [mi	192.3243	113.0431	151.8872	243.2543	203.7319	188.2645	868.2064	552.092	481.6615	675.9932	697.026	565.5983	
14	TOTEXx [n	113.5975	77.18999	97.80533	172.1399	128.4407	141.1346	481.2291	352.3503	288.3349	441.9631	386.4927	363.9059	
15	TOTEXy [n	131.3487	66.85932	94.99541	139.409	130.2177	96.19407	626.2311	353.1698	314.1412	415.7012	505.4879	365.5571	
16	MVELO [m	3.205405	1.884051	2.531453	4.054238	3.395531	3.137742	14.47011	9.201533	8.027691	11.26655	11.6171	9.426639	
17	MVELOx [i	1.893291	1.2865	1.630089	2.868999	2.140679	2.352244	8.020485	5.872505	4.805581	7.366051	6.441545	6.065099	
18	MVELOy [i	2.189145	1.114322	1.583257	2.323484	2.170294	1.603234	10.43719	5.886164	5.235687	6.928354	8.424798	6.092618	
19	CEA [mm^	47.59042	39.68616	58.17797	77.20684	42.53319	67.25528	306.3051	199.4406	170.3811	214.0321	242.606	163.2247	
20	M [mm]	6.247465	4.818547	8.104363	7.544343	4.602561	6.913994	11.11708	10.03969	9.474244	8.663981	9.447003	8.343807	
21	m [mm]	2.424744	2.62164	2.285019	3.257501	2.941566	3.096332	8.770284	6.323293	5.72436	7.863419	8.174431	6.226898	
22	b1	-0.54991	-0.34608	-0.1779	0.239627	1.213908	0.194424	0.619607	0.200316	-0.12656	-0.80711	1.274948	0.701528	
23	b2	1.818487	2.889476	5.621279	-4.17316	-0.82379	-5.14341	-1.61393	-4.99211	7.901711	1.238996	-0.78435	-1.42546	
24	e	0.92161	0.839038	0.959429	0.901979	0.769111	0.894116	0.614519	0.776733	0.796831	0.419839	0.501266	0.665621	
25	Lambda 1	6.513598	3.874765	10.96102	9.498524	3.535186	7.977581	20.62503	16.82108	14.97968	12.52704	14.89366	11.61828	
26	Lambda 2	0.981171	1.14699	0.87135	1.770852	1.444011	1.599957	12.83632	6.672674	5.468487	10.31897	11.15137	6.470782	

Figure 33: IBEOEC Macro with values.

7. Save file: XXXX_IBEOEC_result.xlsx
Location: Y:\Research-GraduatePrograms\RehabSciencesProjects\Biomechanics\Sheri Silfies\Marisa’s Projects\Legacy Fund\Subjects\XXXX\RESULT

Operational Definitions of Force Variables
(Figure 34)

95% confidence ellipse area (CEA): area of 95% confidence ellipse (see picture), in mm^2
Max Tz: Maximum torque about the Z-axis
MD: Average directional control, in mm
TP: target precision, in mm^2

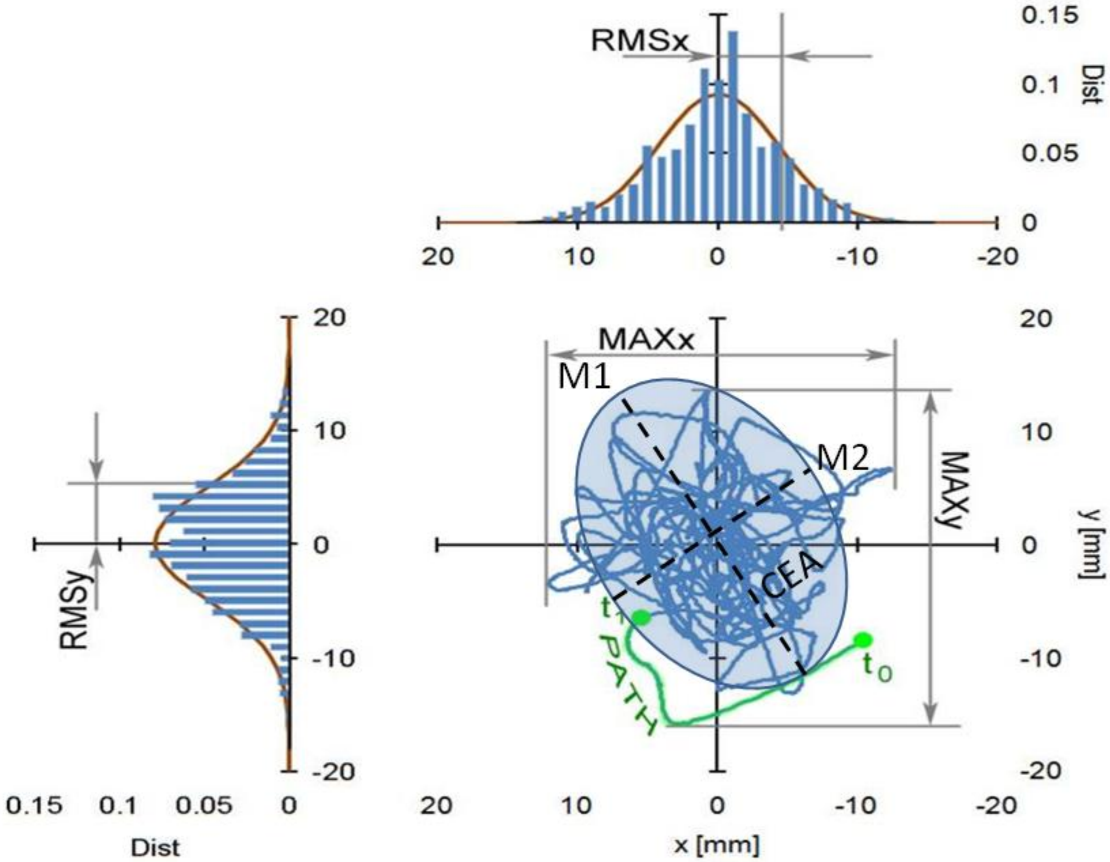


Figure 34: Force plate variables.

Appendix 10.

Formal Survey Email to Expert Panel – Survey #1

Dear Colleague,

You are invited to participate in a research study titled "Survey of Opinions on Athletic Screening Tests." Courtney Butowicz MSEd, CSCS, PhD candidate at Drexel University and her advisor, have developed this study and the following survey. The survey is designed to aggregate professional opinions on the value of commonly used clinical musculoskeletal screening assessments. The assessments within the survey are screening tests that are being considered for inclusion in a comprehensive pre-participation athletic screen tool. The goal of this survey is to determine expert's opinions on the constructs of each assessment, the primary body region being assessed, the primary deviations from expected performance of the assessment, and the value of movement symmetry within specific assessments. This information will be used to help identify a smaller number of tests that will be investigated for use in a comprehensive screen of athletes.

You are being invited to complete the survey because you have been identified as someone who actively screens athletes and/or treats athletic injuries. In this study, you are being asked to complete an electronic survey. Your participation in this study is voluntary and you are free to withdraw your participation at any time. The survey should take 30-40 minutes to complete.

The survey collects no identifying information of any respondent. All of the response in the survey will be recorded anonymously. Absolutely no personal information will be asked of you, nor will any personal information be recorded. The link to the survey provided below will take you directly to the survey. Please note, your computer's IP address will NOT be recorded.

Please click on the link below to complete the survey. We are requesting your input no later than two weeks from today (XX/XX/XXXX).

Link:

Thank you very much for your time and assistance with this project.
Courtney Butowicz, MSEd, CSCS, Doctoral Candidate, Drexel University
Advisor Dr. Sheri Silifes, Department of Rehabilitation Sciences, Drexel University

Formal Survey Email to Expert Panel – Survey #2

Dear Colleague,

You are invited to participate in a research study titled "Survey of Opinions on Athletic Screening Tests." Courtney Butowicz MSEd, CSCS, PhD candidate at Drexel University and her advisor, have developed the following survey.

The survey is designed to aggregate professional opinions on the value of commonly used clinical musculoskeletal screening assessments. The assessments within the survey are screening tests that are being considered for inclusion in a comprehensive pre-participation athletic screen tool. The goal of this survey is to determine experts' opinions on which tests should be included in a comprehensive athletic screen, based on information regarding test constructs and anatomic regions assessed gathered from a previous survey. This information will be used to help identify a smaller number of tests that will be investigated for use in a comprehensive screen of athletes.

You are being invited to complete the survey because you have been identified as someone who actively screens athletes and/or treats athletic injuries. In this study, you are being asked to complete an electronic survey. Your participation in this study is voluntary and you are free to withdraw your participation at any time. The survey should take approximately 15 minutes to complete.

The survey collects no identifying information of any respondent. All of the response in the survey will be recorded anonymously. Absolutely no personal information will be asked of you, nor will any personal information be recorded. The link to the survey provided below will take you directly to the survey. Please note, your computer's IP address will not be provided to the researchers.

Please click on the link below to complete the survey. We are requesting your input no later than one week from today (XX/XX/XXXX).

Thank you very much for your time and assistance with this project.

Courtney Butowicz, MSEd, CSCS, Doctoral Candidate
Dr. Sheri Silfies, Advisor
Department of Rehabilitation Sciences
Drexel University

Appendix 11. Survey #1

Pre-participation clinical screening tools-Survey #1

Q166 The following survey is designed to gather professional opinions on the value of commonly used clinical athletic screening assessments. The tests included in this survey are part of a comprehensive pre-participation athletic screen. The goal of this process is to determine expert's opinions on the constructs each test is assessing, the primary body regions being assessed, the primary deviations from expected performance, and the value of performance symmetry within certain tests. Please keep in mind, the tests contained in this survey are part of a comprehensive pre-participation screen for athletes that is aiming to detect "big red flags." This screen is NOT meant to diagnose, but rather, identify performance degradations that may increase injury risk. All tests that are described unilaterally, are performed bilaterally during actual screening. All responses to this survey are anonymous. The researchers will only receive aggregate responses. This survey will take approximately 30-40 minutes. You may start, stop, and return to the survey as many times as you would like until it is completed in full. We thank you very much for taking the time to complete the survey!

Q3 This test is performed with the athlete lying on their side, body in a straight line, legs stacked on top of each other, knees straight and toes pulled towards the shins. Athlete is instructed to lift the top leg toward the ceiling as high as they can, while maintaining body positioning and the top leg over the bottom leg. In your opinion, which of the following constructs is this test primarily assessing? Stability: The ability to control the body region's position in order to withstand internal and external perturbations Mobility: Range of motion within one or multiple joints Movement pattern efficiency: the coordination of motion (timing and amount) between segments and/or extremities that demonstrates effective acceptance, generation, or transfer of forces to accomplish a skill or task. For bilateral tasks, this includes equal motion and weight bearing through the extremities

- ❍ Stability (1)
- ❍ Mobility (2)
- ❍ Movement Pattern Efficiency (3)

If Mobility Is Selected, Then Skip To Which of the following body regions i...

Q1 Would you classify/categorize this test as primarily a test of: Neuromuscular control: the ability to accurately orchestrate a syncronized muscular response to internal and external perturbations based on sensory feedback Muscle capacity/performance: strength, endurance, or power of the involved musculature

- ❑ Neuromuscular Control (1)
- ❑ Muscle Capacity/Performance (2)
- ❑ Mobility (3)
- ❑ None of these (4)

Q4 Which of the following body regions is this test primarily assessing? (you may check more than one answer)

- ❑ Trunk/Pelvis (1)
- ❑ Hip (2)
- ❑ Lower Extremity (3)

Q2 Do you think a difference in performance between sides is meaningful?

- ❍ Yes (1)
- ❍ No (2)

Answer If Do you think a difference in performance between sides is meaningful? Yes Is Selected

Q164 You answered yes, a performance difference between sides is meaningful, what amount of difference would you consider meaningful? Subtle: Questionable or mild differences between sides Obvious: Marked or clear differences between sides

- ❍ Subtle (1)
- ❍ Obvious (2)

Q5 Based on the following deviations from the expected performance of this test, drag over the TWO you would consider the most important and in ORDER of importance.

Click to write Group 1
______ Hip does not remain in neutral (1)
______ Pelvis does not remain in neutral (2)
______ Spine does not remain in neutral (3)
______ Any trunk movement prior to, during, or after hip ABD (4)

Q8 This is the same test as the previous question, however, now the tester will apply manual resistance proximal to the lateral malleolus once the top leg is parallel to the ground. The athlete is instructed to maintain hip position and alignment against resistance. In your opinion, which of the following constructs is this test primarily assessing? Stability: The ability to control the body region's position in order to withstand internal and external perturbations Mobility: Range of motion within one or multiple joints Movement pattern efficiency: the coordination of motion (timing and amount) between segments and/or extremities that demonstrates effective acceptance, generation, or transfer of forces to accomplish a skill or task. For bilateral tasks, this includes equal motion and weight bearing through the extremities

- ❍ Stability (1)
- ❍ Mobility (2)
- ❍ Movement Pattern Efficiency (3)

If Mobility Is Selected, Then Skip To Which of the following body regions i...

Q9 Would you classify/categorize this test as primarily a test of: Neuromuscular control: the ability to accurately orchestrate a syncronized muscular response to internal and external perturbations based on sensory feedback Muscle capacity/performance: strength, endurance, or power of the involved musculature

- ❍ Neuromuscular Control (1)
- ❍ Muscle Capacity/Performance (2)
- ❍ Mobility (3)
- ❍ None of these (4)

Q10 Which of the following body regions is this test primarily assessing? (you may check more than one answer)

- ❑ Trunk/Pelvis (1)
- ❑ Hip (2)
- ❑ Lower Extremity (3)

Q11 Do you think a difference in performance between sides is meaningful?
- ❍ Yes (1)
- ❍ No (2)

Answer If Do you think a difference in performance between sides is meaningful? Yes Is Selected
Q165 You answered yes, a performance difference between sides is meaningful, what amount of difference would you consider meaningful? Subtle: Questionable or mild differences between sidesObvious: Marked or clear differences between sides
- ❍ Subtle (1)
- ❍ Obvious (2)

Q12 Based on the following deviations from the expected performance of this test, drag over the TWO you would consider the most important and in ORDER of importance.

Click to write Group 1
______ Hip does not remain in neutral (1)
______ Pelvis does not remain in neutral (2)
______ Spine does not remain in neutral (3)
______ any trunk movement prior to, during, or after hip ABD (4)

Q13 This test is performed with the athlete lying on their side, propped up on their forearm with the shoulder over the elbow and the bottom knee bent to 90 degrees. The top and bottom thighs should be in line with one another, the top leg straight, and toes pulled towards the shins. From here, the ahtlete is instructed to lift their pelvis off the table until their head, spine, and bottom leg are in a straight line.   In your opinion, which of the following constructs is this test primarily assessing?   Stability: The ability to control the body region's position in order to withstand internal and external perturbations   Mobility: Range of motion within one or multiple joints   Movement pattern efficiency: the coordination of motion (timing and amount) between segments and/or extremities that demonstrates effective acceptance, generation, or transfer of forces to accomplish a skill or task. For bilateral tasks, this includes equal motion and weight bearing through the extremities
- ❍ Stability (1)
- ❍ Mobility (2)
- ❍ Movement pattern efficiency (3)

If Mobility Is Selected, Then Skip To Which of the following body regions i...

Q38 Would you classify/categorize this test as primarily a measure of: Neuromuscular control: the ability to accurately orchestrate a syncronized muscular response to internal and external perturbations based on sensory feedback Muscle capacity/performance: strength, endurance, or power of the involved musculature
- ❍ Neuromuscular Control (1)
- ❍ Muscle capacity/peformance (2)
- ❍ Mobility (3)

❍ None of these (4)

Q39 Which of the following body regions is this test primarily assessing?
❍ Trunk/pelvis (1)
❍ Shoulder (2)
❍ Lower extremity (3)

Q40 Do you think a difference in performance between sides is meaningful?
❍ Yes (1)
❍ No (2)

Answer If Do you think a difference in performance between sides is meaningful? If yes, what amount of difference would be meaningful? Yes Is Selected
Q41 You answered yes, a performance difference between sides is meaningful, what amount of difference would you consider meaningful? Subtle: Questionable or mild differences between sidesObvious: Marked or clear differences between sides
❍ Subtle (1)
❍ Obvious (2)

Q42 Based on the following deviations from the expected performance of this test, drag over the TWO you would consider the most important and in ORDER of importance.

Click to write Group 1
______ Hip does not remain in neutral (1)
______ Pelvis does not remain in neutral (2)
______ Spine does not remain in neutral (3)
______ any trunk movement prior to bridge (4)

Q12 While maintaining the side bridge position established in the last test, the athlete is instructed to raise their top leg toward the ceiling as high as they can while maintaining alignment. In your opinion, which of the following constructs is this test primarily assessing? Stability: The ability to control the body region's position in order to withstand internal and external perturbations Mobility: Range of motion within one or multiple joints Movement pattern efficiency: the coordination of motion (timing and amount) between segments and/or extremities that demonstrates effective acceptance, generation, or transfer of forces to accomplish a skill or task. For bilateral tasks, this includes equal motion and weight bearing through the extremities
❍ Stability (1)
❍ Mobility (2)
❍ Movement Pattern Efficiency (3)
If Mobility Is Selected, Then Skip To Which of the following body regions i...

Q43 Would you classify/categorize this test as primarily a measure of: Neuromuscular control: the ability to accurately orchestrate a syncronized muscular response to internal and external perturbations based on sensory feedback Muscle capacity/performance: strength, endurance, or power of the involved musculature

- Neuromuscular control (1)
- Muscle capacity/performance (2)
- Mobility (3)
- None of these (4)

Q44 Which of the following body regions is this test primarily assessing?

- Trunk/Pelvis (1)
- Shoulder (2)
- Lower Extremity (3)

Q45 Do you think a difference in performance between sides is meaningful?

- Yes (1)
- No (2)

Answer If Do you think a difference in performance between sides is meaningful? If yes, what amount of difference would be meaningful? Yes Is Selected
Q46 You answered yes, a performance difference between sides is meaningful, what amount of difference would would you consider meaningful? Subtle: Questionable or mild differences between sidesObvious: Marked or clear differences between sides

- Subtle (1)
- Obvious (2)

Q47 Based on the following deviations from the expected performance of this test, drag over the TWO you would consider the most important and in ORDER of importance.

Click to write Group 1
______ Hip does not remain in neutral (1)
______ Pelvis does not remain in neutral (2)
______ Spine does not remain in neutral (3)
______ any trunk movement prior to, during, or after hip ABD (4)

Q13 Once the side bridge position from the previous test is established, the athlete is instructed to lift their top leg until it is paralell to the table. From this position, the tester applies manual resistance proximal to the lateral malleolus. Athlete should maintain trunk alignment and leg position.   In your opinion, which of the following constructs is this test primarily assessing?   Stability: The ability to control the body region's position in order to withstand internal and external perturbations   Mobility: Range of motion within one or multiple joints   Movement pattern efficiency: the coordination of motion (timing and amount) between segments and/or extremities that demonstrates effective acceptance, generation, or transfer of forces to accomplish a skill or task. For bilateral tasks, this includes equal motion and weight bearing through the extremities

- Stability (1)
- Mobility (2)

❍ Movement pattern efficiency (3)
If Mobility Is Selected, Then Skip To Which of the following body regions i...

Q48 Would you classify/categorize this test as primarily a measure of: Neuromuscular control: the ability to accurately orchestrate a syncronized muscular response to internal and external perturbations based on sensory feedback Muscle capacity/performance: strength, endurance, or power of the involved musculature
❍ Neuromuscular Control (1)
❍ Muscle capacity/performance (2)
❍ Mobility (3)
❍ None of these (4)

Q49 Which of the following body regions is this test primarily assessing? (you may select more than one)
❑ Trunk/Pelvis (1)
❑ Shoulder (2)
❑ Lower Extremity (3)

Q50 Do you think a difference in performance between sides is meaningful?
❍ Yes (1)
❍ No (2)

Answer If Do you think a difference in performance between sides is meaningful? If yes, what amount of difference would be meaningful? Yes Is Selected
Q51 You answered yes, a performance difference between sides is meaningful, what amount of difference would would you consider meaningful? Subtle: Questionable or mild differences between sidesObvious: Marked or clear differences between sides
❍ Subtle (1)
❍ Obvious (2)

Q52 Based on the following deviations from the expected performance of this test, drag over the TWO you would consider the most important and in ORDER of importance.

Click to write Group 1
______ Hip does not remain in neutral (1)
______ Pelvis does not remain in neutral (2)
______ Spine does not remain in neutral (3)
______ any trunk movement prior to, during, or after hip ABD (4)

Q14 This test is performed by instructing the athlete to sit on the edge of the table, lie back while pulling both knees to the chest. While holding the left knee to the chest, the athlete will lower the right leg toward the table until they are fully relaxed. In your opinion, which of the following constructs is this test primarily assessing? Stability: The ability to control the body region's position in order to withstand internal and external perturbations Mobility: Range of motion within one or multiple joints Movement pattern efficiency: the coordination of motion (timing and amount) between segments and/or extremities that demonstrates effective acceptance, generation, or transfer of forces to accomplish a skill or task. For bilateral tasks, this includes equal motion and weight bearing through the extremities

- ❍ Stability (1)
- ❍ Mobility (2)
- ❍ Movement pattern efficiency (3)

If Mobility Is Selected, Then Skip To Which of the following body regions i...

Q53 Would you classify/categorize this test as primarily a measure of: Neuromuscular control: the ability to accurately orchestrate a syncronized muscular response to internal and external perturbations based on sensory feedback Muscle capacity/performance: strength, endurance, or power of the involved musculature

- ❍ Neuromuscular Control (1)
- ❍ Muscle capacity/performance (2)
- ❍ Mobility (3)
- ❍ None of these (4)

Q54 Which of the following body regions is this test primarily assessing?

- ❍ Trunk/Pelvis (1)
- ❍ Lower extremity (2)
- ❍ Both (3)

Q55 Do you think a difference in performance between sides is meaningful?

- ❍ Yes (1)
- ❍ No (2)

Answer If Do you think a difference in performance between sides is meaningful? If yes, what amount of difference would be meaningful? Yes Is Selected
Q56 You answered yes, a performance difference between sides is meaningful, what amount of difference would would you consider meaningful? Subtle: Questionable or mild differences between sidesObvious: Marked or clear differences between sides

- ❍ Subtle (1)
- ❍ Obvious (2)

Q60 Based on the following deviations from the expected performance of this test, drag over the TWO you would consider the most important and in ORDER of importance.

Click to write Group 1
______ Thigh does not contact the table (1)
______ Thigh contacts the table, but knee does not achieve 80 degrees of flexion (2)
______ Head and trunk does not remain neutral (3)

Q15 This test is performed by instructing the athlete to lie flat with the back of their knees against the board and toes pulled toward the shins. With both arms next to the body, palms facing up, they will raise their left foot as high as possible while keeping the left leg straight and the right knee against the board. Testers determine the location of the raised ankle relative to the stationary leg.   In your opinion, which of the following constructs is this test primarily assessing?   Stability: The ability to control the body region's position in order to withstand internal and external perturbations   Mobility: Range of motion within one or multiple joints   Movement pattern efficiency: the coordination of motion (timing and amount) between segments and/or extremities that demonstrates effective acceptance, generation, or transfer of forces to accomplish a skill or task. For bilateral tasks, this includes equal motion and weight bearing through the extremities

- Stability (1)
- Mobility (2)
- Movement pattern efficiency (3)

If Mobility Is Selected, Then Skip To Which of the following body regions i...

Q16 Would you classify/categorize this test as primarily a measure of: Neuromuscular control: the ability to accurately orchestrate a syncronized muscular response to internal and external perturbations based on sensory feedback Muscle capacity/performance: strength, endurance, or power of the involved musculature

- Neuromuscular Control (1)
- Muscle capacity/performance (2)
- Mobility (3)
- None of these (4)

Q57 Which of the following body regions is this test primarily assessing?

- Trunk/pelvis (1)
- Lower extremity (2)
- Both (3)

Q58 Do you think a difference in performance between sides is meaningful?

- Yes (1)
- No (2)

Answer If Do you think a difference in performance between sides is meaningful? If yes, what amount of difference would be meaningful? Yes Is Selected

Q59 You answered yes, a performance difference between sides is meaningful, what amount of difference would would you consider meaningful? Subtle: Questionable or mild differences between sides (less than 10 degrees)Obvious: Marked or clear differences between sides (more than 10 degrees)

- Subtle (1)
- Obvious (2)

Q61 Based on the following deviations from the expected performance of this test, drag over the TWO you would consider the most important and in ORDER of importance.

Click to write Group 1
______ Non-moving leg does not remain stationary and in touch with the board (1)

______ Head does not remain flat on floor (2)
______ Pelvis does not remain in neutral (3)
______ Trunk does not remain in neutral (4)

Q17 This test is performed by instructing the athlete to lie on their back, knees bent to 90 degrees, feet hip width apart, and arms across their chest. From this position, they will lift their hips off the table/floor until their body is in a straight line. From this position, they are instructed to hold this alignment as they straighten their left leg. In your opinion, which of the following constructs is this test primarily assessing? Stability: The ability to control the body region's position in order to withstand internal and external perturbations Mobility: Range of motion within one or multiple joints Movement pattern efficiency: the coordination of motion (timing and amount) between segments and/or extremities that demonstrates effective acceptance, generation, or transfer of forces to accomplish a skill or task. For bilateral tasks, this includes equal motion and weight bearing through the extremities
- ❍ Stability (1)
- ❍ Mobility (2)
- ❍ Movement pattern efficiency (3)

If Mobility Is Selected, Then Skip To Which of the following body regions i...

Q62 Would you classify/categorize this test as primarily a measure of: Neuromuscular control: the ability to accurately orchestrate a syncronized muscular response to internal and external perturbations based on sensory feedback Muscle capacity/performance: strength, endurance, or power of the involved musculature
- ❍ Neuromuscular Control (1)
- ❍ Muscle capacity/performance (2)
- ❍ Mobility (3)
- ❍ None of these (4)

Q63 Which of the following body regions is this test primarily assessing?
- ❍ Trunk/Pelvis (1)
- ❍ Lower Extremity (2)
- ❍ Both (3)

Q64 Do you think a difference in performance between sides is meaningful?
- ❍ Yes (1)
- ❍ No (2)

Answer If Do you think a difference in performance between sides is meaningful? If yes, what amount of difference would be meaningful? Yes Is Selected
Q65 You answered yes, a performance difference between sides is meaningful, what amount of difference would would you consider meaningful? Subtle: Questionable or mild differences between sidesObvious: Marked or clear differences between sides
- ❍ Subtle (1)
- ❍ Obvious (2)

Q66 Based on the following deviations from the expected performance of this test, drag over the TWO you would consider the most important and in ORDER of importance.

Click to write Group 1
______ Loss of hip extension with knee extension (1)
______ Loss of neutral pelvis during task (2)
______ Loss of neutral spine during task (3)

Q18 This test is performed the same as the previous test, however, once the leg is extended, the tester applies a manual resistance proximal to the ankle of the extended leg. Athlete is instructed to maintain trunk and pelvis alignment. In your opinion, which of the following constructs is this test primarily assessing? Stability: The ability to control the body region's position in order to withstand internal and external perturbations Mobility: Range of motion within one or multiple joints Movement pattern efficiency: the coordination of motion (timing and amount) between segments and/or extremities that demonstrates effective acceptance, generation, or transfer of forces to accomplish a skill or task. For bilateral tasks, this includes equal motion and weight bearing through the extremities

- ❍ Stability (1)
- ❍ Mobility (2)
- ❍ Movement pattern efficiency (3)

If Mobility Is Selected, Then Skip To Which of the following body regions i...

Q67 Would you classify/categorize this test as primarily a measure of: Neuromuscular control: the ability to accurately orchestrate a syncronized muscular response to internal and external perturbations based on sensory feedback Muscle capacity/performance: strength, endurance, or power of the involved musculature

- ❍ Neuromuscular control (1)
- ❍ Muscle capacity/performance (2)
- ❍ Mobility (3)
- ❍ None of these (4)

Q68 Which of the following body regions is this test primarily assessing?

- ❍ Trunk/pelvis (1)
- ❍ lower extremity (2)
- ❍ Both (3)

Q69 Do you think a difference in performance between sides is meaningful?

- ❍ Yes (1)
- ❍ No (2)

Answer If Do you think a difference in performance between sides is meaningful? If yes, what amount of difference would be meaningful? Yes Is Selected

Q70 You answered yes, a performance difference between sides is meaningful, what amount of difference would would you consider meaningful? Subtle: Questionable or mild differences between sidesObvious: Marked or clear differences between sides

- ❍ Subtle (1)
- ❍ Obvious (2)

Q71 Based on the following deviations from the expected performance of this test, drag over the TWO you would consider the most important and in ORDER of importance.

Click to write Group 1
______ Loss of hip extension with knee extension (1)
______ Loss of neutral pelvis (2)
______ Loss of neutral spine (3)
______ Amount of hip extension decreases with increased task difficulty (4)

Q19 This test is performed by having the athlete assume a single-leg hip bridge position. A mobilization belt with a digital inclinometer attached to it is secured to the athlete's waist (the belt should be in contact with both ASIS). The athlete is instructed to maintain this position as long as they can. The inclinometer measures the amount of transverse or sagittal plane movement of the pelvis. Once the athlete moves at least 10 degrees in either plane from the start position (neutral), the test is terminated and the amount of time in the single-leg position is recorded.   In your opinion, which of the following constructs is this test primarily assessing?   Stability: The ability to control the body region's position in order to withstand internal and external perturbations   Mobility: Range of motion within one or multiple joints   Movement pattern efficiency: the coordination of motion (timing and amount) between segments and/or extremities that demonstrates effective acceptance, generation, or transfer of forces to accomplish a skill or task. For bilateral tasks, this includes equal motion and weight bearing through the extremities

- ❍ Stability (1)
- ❍ Mobility (2)
- ❍ Movement pattern efficiency (3)

If Mobility Is Selected, Then Skip To Which of the following body regions i...

Q73 Would you classify/categorize this test as primarily a measure of: (you may pick more than one) Neuromuscular control: the ability to accurately orchestrate a syncronized muscular response to internal and external perturbations based on sensory feedback Muscle capacity/performance: strength, endurance, or power of the involved musculature

- ❍ Neuromuscular control (1)
- ❍ Muscle capacity/performance (2)
- ❍ Mobiilty (3)
- ❍ None of these (4)

Q74 Which of the following body regions is this test primarily assessing?

- ❍ Trunk/pelvis (1)
- ❍ lower extremity (2)
- ❍ Both (3)

Q75 Do you think a difference in performance between sides is meaningful?
- ❍ Yes (1)
- ❍ No (2)

Answer If Do you think a difference in performance between sides is meaningful? If yes, what amount of difference would be meaningful? Yes Is Selected
Q76 You answered yes, a performance difference between sides is meaningful, what amount of difference would would you consider meaningful? Subtle: less than a 20% difference in time between sidesObvious: more than a 20% difference in time between sides
- ❍ Subtle (1)
- ❍ Obvious (2)

Q77 Based on the following deviations from the expected performance of this test, drag over the TWO you would consider the most important and in ORDER of importance.

Click to write Group 1
______ A 10 degree loss in neutral pelvis in transverse or sagittal plane (1)
______ A 15 degree loss in neutral pelvis in transverse or sagittal plane (2)
______ Loss of neutral spine position (3)

Q20 This test is performed by instructing the athlete to lie on their stomach with their hands under their forehead and their feet hanging off the edge of the table. From this position, they are instructed to lift their leg until their thigh comes just off the table.   In your opinion, which of the following constructs is this test primarily assessing?   Stability: The ability to control the body region's position in order to withstand internal and external perturbations   Mobility: Range of motion within one or multiple joints   Movement pattern efficiency: the coordination of motion (timing and amount) between segments and/or extremities that demonstrates effective acceptance, generation, or transfer of forces to accomplish a skill or task. For bilateral tasks, this includes equal motion and weight bearing through the extremities
- ❍ Stabilty (1)
- ❍ Mobility (2)
- ❍ Movement pattern efficiency (3)

If Mobility Is Selected, Then Skip To Which of the following body regions i...

Q78 Would you classify/categorize this test as primarily a measure of: Neuromuscular control: the ability to accurately orchestrate a syncronized muscular response to internal and external perturbations based on sensory feedback Muscle capacity/performance: strength, endurance, or power of the involved musculature
- ❍ Neuromuscular control (1)

- ❍ Muscle capacity/performance (2)
- ❍ Mobility (3)
- ❍ None of these (4)

Q79 Which of the following body regions is this test assessing?
- ❍ Trunk/Pelvis (1)
- ❍ Lower Extremity (2)
- ❍ Both (3)

Q80 Do you think a difference in performance between sides is meaningful?
- ❍ Yes (1)
- ❍ No (2)

Answer If Do you think a difference in performance between sides is meaningful? If yes, what amount of difference would be meaningful? Yes Is Selected
Q81 You answered yes, a performance difference between sides is meaningful, what amount of difference would would you consider meaningful? Subtle: Questionable or mild differences between sidesObvious: Marked or clear differences between sides
- ❍ Subtle (1)
- ❍ Obvious (2)

Q82 Based on the following deviations from the expected performance of this test, drag over the TWO you would consider the most important and in ORDER of importance.

Click to write Group 1
______ Inability to lift thigh off table (1)
______ Hip internal/external rotation (2)
______ Loss of neutral spine/pelvis (3)
______ Picking up head (4)

Q21 This test is performed by having the athlete start in the same start position as the previous test. The athlete will straighten and raise one arm and then raise the contralateral leg until the thigh is just off the table.   In your opinion, which of the following constructs is this test primarily assessing?   Stability: The ability to control the body region's position in order to withstand internal and external perturbations   Mobility: Range of motion within one or multiple joints   Movement pattern efficiency: the coordination of motion (timing and amount) between segments and/or extremities that demonstrates effective acceptance, generation, or transfer of forces to accomplish a skill or task. For bilateral tasks, this includes equal motion and weight bearing through the extremities
- ❍ Stability (1)
- ❍ Mobility (2)
- ❍ Movement pattern efficiency (3)

If Mobility Is Selected, Then Skip To Which of the following body regions i...

Q83 Would you classify/categorize this test as primarily a measure of: Neuromuscular control: the ability to accurately orchestrate a syncronized muscular response to internal and external perturbations based on sensory feedback Muscle capacity/performance: strength, endurance, or power of the involved musculature

- Neuromuscular control (1)
- Muscle capacity/performance (2)
- Mobility (3)
- None of these (4)

Q84 Which of the following body regions is this test primarily assessing?

- Trunk/Pelvis (1)
- Lower extremity (2)
- Upper extremity (3)

Q85 Do you think a difference in performance between sides is meaningful?

- Yes (1)
- No (2)

Answer If Do you think a difference in performance between sides is meaningful? If yes, what amount of difference would be meaningful? Yes Is Selected
Q86 You answered yes, a performance difference between sides is meaningful, what amount of difference would would you consider meaningful? Subtle: Questionable or mild differences between sidesObvious: Marked or clear differences between sides

- Subtle (1)
- Obvious (2)

Q87 Based on the following deviations from the expected performance of this test, drag over the TWO you would consider the most important and in ORDER of importance.

Click to write Group 1
______ Inability to lift thigh off table (1)
______ Hip external/internal rotation (2)
______ Loss of neutral spine/pelvis (3)
______ Picking up head (4)

Q173 This test is performed by instructing the athlete to assume a quadruped position, rock their hips back towards their heels, lower their chest to their knees, and reach their hands in front of them as far as possible. Testers should observe for pain or limited/excessive motion.   In your opinion, which of the following constructs is this test primarily assessing?   Stability: The ability to control the body region's position in order to withstand internal and external perturbations   Mobility: Range of motion within one or multiple joints   Movement pattern efficiency: the coordination of motion (timing and amount) between segments and/or extremities that demonstrates effective acceptance, generation, or transfer of forces to accomplish a skill or task. For bilateral tasks, this includes equal motion and weight bearing through the extremities

❍ Stability (1)
❍ Mobility (2)
❍ Movement Pattern Efficiency (3)
If Mobility Is Selected, Then Skip To Which of the following body regions i...

Q174 Would you classify/categorize this test as primarily a measure of:Neuromuscular control: the ability to accurately orchestrate a syncronized muscular response to internal and external perturbations based on sensory feedbackMuscle capacity/performance: strength, endurance, or power of the involved musculature
❍ Neuromuscular Control (1)
❍ Mobility (2)
❍ Muscle capacity/performance (3)

Q175 Which of the following body regions is this test primarily assessing? (you may select more than one)
❑ Trunk/Pelvis (1)
❑ Upper Extremity (2)
❑ Lower Extremity (3)

Q176 Based on the following deviations from the expected performance of this test, drag over the TWO you would consider the most important.

Click to write Group 1
______ Limited motion (1)
______ Excessive motion (2)
______ Pain (3)

Q167 This test is performed by having the athlete assume a quadruped position over the board with the toes, knees, and thumbs touching the board. The hands should be under the shoulders and the knees under the hips. From this position, they are instructed to reach the left hand forward and the right leg back at the same time, until they come about 6 inches off the ground. Then, without touching down, they should touch the left elbow to the right knee over the board, return to the extended position and then return to the start position (quadruped). In your opinion, which of the following constructs is this test primarily assessing? Stability: The ability to control the body region's position in order to withstand internal and external perturbations Mobility: Range of motion within one or multiple joints Movement pattern efficiency: the coordination of motion (timing and amount) between segments and/or extremities that demonstrates effective acceptance, generation, or transfer of forces to accomplish a skill or task. For bilateral tasks, this includes equal motion and weight bearing through the extremities
❍ Stability (1)
❍ Mobility (2)
❍ Movement Pattern Efficiency (3)
If Mobility Is Selected, Then Skip To Which of the following body regions i...

Q168 Would you classify/categorize this test as primarily a measure of:Neuromuscular control: the ability to accurately orchestrate a syncronized muscular response to internal and external perturbations based on sensory feedbackMuscle capacity/performance: strength, endurance, or power of the involved musculature

- ❍ Neuromuscular Control (1)
- ❍ Muscle Capacity/Performance (2)
- ❍ Mobility (3)

Q169 Which of the following body regions is this test primarily assessing? (you may select more than one)

- ❑ Upper Extremity (1)
- ❑ Lower Extremity (2)
- ❑ Trunk/Pelvis (3)

Q170 Do you think a difference in performance between sides is meaningful?

- ❍ Yes (1)
- ❍ No (2)

Answer If Do you think a difference in performance between sides is meaningful? Yes Is Selected
Q171 You answered yes, a performance difference between sides is meaningful, what amount of difference would would you consider meaningful? Subtle: Questionable or mild differences between sidesObvious: Marked or clear differences between sides

- ❍ Subtle (1)
- ❍ Obvious (2)

Q172 Based on the following deviations from the expected performance of this test, drag over the ONE you would consider the most important.

Click to write Group 1
______ Inability to control trunk/pelvis movement (1)
______ Loss of balance (2)

Q22 This test is performed by having the athlete assume a quadruped position over the board with the toes, knees, and thumbs touching the board. The hands should be under the shoulders and the knees under the hips. From this position, they are instructed to reach the left hand forward and the left leg back at the same time, until they come about 6 inches off the ground. Then, without touching down, they should touch the left elbow to the left knee over the board, return to the extended position and then return to the start position (quadruped).   In your opinion, which of the following constructs is this test primarily assessing?   Stability: The ability to control the body region's position in order to withstand internal and external perturbations   Mobility: Range of motion within one or multiple joints   Movement pattern efficiency: the coordination of motion (timing and amount) between segments and/or extremities that demonstrates effective acceptance, generation, or transfer of forces to accomplish a skill or task. For bilateral tasks, this includes equal motion and weight bearing through the extremities

- Stability (1)
- Mobility (2)
- Movement Pattern Efficiency (3)

If Mobility Is Selected, Then Skip To Which of the following body regions i...

Q88 Would you classify/categorize this test as primarily a measure of: Neuromuscular control: the ability to accurately orchestrate a syncronized muscular response to internal and external perturbations based on sensory feedback Muscle capacity/performance: strength, endurance, or power of the involved musculature

- Neuromuscular control (1)
- Muscle capacity/performance (2)
- Mobility (3)
- None of these (4)

Q89 Which of the following body regions is this test primarily assessing? (you may select more than one)

- ❑ Trunk/Pelvis (1)
- ❑ Lower Extremity (2)
- ❑ Upper extremity (3)

Q90 Do you think a difference in performance between sides is meaningful?

- Yes (1)
- No (2)

Answer If Do you think a difference in performance between sides is meaningful? If yes, what amount of difference would be meaningful? Yes Is Selected
Q91 You answered yes, a performance difference between sides is meaningful, what amount of difference would would you consider meaningful? Subtle: Questionable or mild differences between sidesObvious: Marked or clear differences between sides

- Subtle (1)
- Obvous (2)

Q92 Based on the following deviations from the expected performance of this test, drag over the ONE you would consider the most important.

Click to write Group 1
______ Inability to control trunk/pelvis during movement (2)
______ Loss of balance (3)

Q177 This test is performed by instructing the athlete to lie on their stomach with their palms down under their shoulders. The athlete is instructed to then press the chest off the floor/table as much as possible by straightening the elbows and allowing no lower body movement. In your opinion, which of the following constructs is this test primarily assessing? Stability: The ability to control the body region's position in order to withstand internal and external perturbations Mobility: Range of motion within one or multiple joints Movement pattern efficiency: the coordination of motion (timing and amount) between segments and/or extremities that demonstrates effective acceptance, generation, or transfer of forces to accomplish a skill or task. For bilateral tasks, this includes equal motion and weight bearing through the extremities

- ❍ Stability (1)
- ❍ Mobility (2)
- ❍ Movement Pattern Efficiency (3)

If Mobility Is Selected, Then Skip To Which of the following body regions i...

Q178 Would you classify/categorize this test as primarily a measure of:Neuromuscular control: the ability to accurately orchestrate a syncronized muscular response to internal and external perturbations based on sensory feedbackMuscle capacity/performance: strength, endurance, or power of the involved musculature

- ❍ Neuromuscular Control (1)
- ❍ Mobility (2)
- ❍ Muscle capacity/performance (3)

Q179 Which of the following body regions is this test primarily assessing? (you may select more than one)

- ❑ Trunk/Pelvis (1)
- ❑ Upper Extremity (2)
- ❑ Lower Extremity (3)

Q180 Based on the following deviations from the expected performance of this test, drag over the TWO you would consider the most important.

Click to write Group 1
______ Limited motion (1)
______ Excessive motion (2)
______ Pain (3)

Q23 This test is performed by instructing the athlete to lie face down with the arms extended overhead and their hands shoulder width apart. The athlete is then instructed to line the thumbs up with the forehead (men) or chin (women). With the legs together, toes pulled towards the shins, the athlete is instructed to lift the body as one unit into the top position of a pushup.   In your opinion, which of the following constructs is this test primarily assessing?   Stability: The ability to control the body region's position in order to withstand internal and external perturbations   Mobility: Range of motion within one or multiple joints   Movement pattern efficiency: the coordination of motion (timing and amount) between segments and/or extremities that demonstrates effective acceptance, generation, or transfer of forces to accomplish a skill or task. For bilateral tasks, this includes equal motion and weight bearing through the extremities

- ❍ Stability (1)
- ❍ Mobility (2)
- ❍ Movement pattern efficiency (3)

If Mobility Is Selected, Then Skip To Which of the following body regions i...

Q93 Would you classify/categorize this test as primarily a measure of: Neuromuscular control: the ability to accurately orchestrate a syncronized muscular response to internal and external perturbations based on sensory feedback Muscle capacity/performance: strength, endurance, or power of the involved musculature

- ❍ Neuromuscular control (1)
- ❍ Muscle capacity/performance (2)
- ❍ Mobility (3)
- ❍ None of these (4)

Q94 Which of the following body regions is this test primarily assessing? (you may select more than one)

- ❑ Trunk/Pelvis (1)
- ❑ Upper extremity (2)
- ❑ Lower extremity (3)

Q97 Based on the following deviations from the expected performance of this test, drag over the TWO you would consider the most important and in ORDER of importance.

Click to write Group 1
______ Body does not lift as one unit (1)
______ Spine goes into extension prior to lifting the body (2)
______ The hands must be adjusted in order to perform the task (3)

Q24 This test is performed by first having the athlete stand with their feet approximately shoulder width apart and toes pointing forward. The athlete will then place the dowel horizontally on their head so the shoulders and elbows are at 90 degrees. They will then press the dowel directly overhead. While maintaining an upright torso, feet flat on the ground, and the dowel overhead, the athlete will squat down as far as possible. They are required to hold the bottom of the squat for one second before returning to standing. In your opinion, which of the following constructs is this test primarily assessing? Stability: The ability to control the body region's position in order to withstand internal and external perturbations Mobility: Range of motion within one or multiple joints Movement pattern efficiency: the coordination of motion (timing and amount) between segments and/or extremities that demonstrates effective acceptance, generation, or transfer of forces to accomplish a skill or task. For bilateral tasks, this includes equal motion and weight bearing through the extremities

- ❍ Stability (1)
- ❍ Mobility (2)
- ❍ Movement pattern efficiency (3)

If Mobility Is Selected, Then Skip To Which of the following body regions i...

Q98 Would you classify/categorize this test as primarily a measure of: Neuromuscular control: the ability to accurately orchestrate a syncronized muscular response to internal and external perturbations based on sensory feedback Muscle capacity/performance: strength, endurance, or power of the involved musculature

- ❍ Neuromuscular control (1)
- ❍ Muscle capacity/performance (2)
- ❍ Mobility (3)
- ❍ None of these (4)

Q99 Which of the following body regions is this test primarily assessing? (you may select more than one)

- ❑ Upper extremity (1)
- ❑ Trunk/Pelvis (2)
- ❑ Lower extremity (3)

Q102 Based on the following deviations from the expected performance of this test, drag over the THREE you would consider the most important and in ORDER of importance.

Click to write Group 1
______ Upper torso is not parallel with tibia OR aligned towards vertical (1)
______ Femur does not go below horizontal (2)
______ Knees are not aligned over the feet (dynamic valgus) (3)
______ Dowel is not aligned over feet (4)
______ Loss of balance or shifting of weight to one side (5)

Q25 This test is performed by instructing the athlete to stand tall with the feet together, toes touching the board, and the dowel behind the neck across the shoulders. While maintaining an upright torso, the athlete will raise the right leg, step over the hurdle, touch the floor with the right heel, and then return to the starting position.   In your opinion, which of the following constructs is this test primarily assessing?   Stability: The ability to control the body region's position in order to withstand internal and external perturbations   Mobility: Range of motion within one or multiple joints   Movement pattern efficiency: the coordination of motion (timing and amount) between segments and/or extremities that demonstrates effective acceptance, generation, or transfer of forces to accomplish a skill or task. For bilateral tasks, this includes equal motion and weight bearing through the extremities

- ❍ Stability (1)
- ❍ Mobility (2)
- ❍ Movement pattern efficiency (3)

If Mobility Is Selected, Then Skip To Which of the following body regions i...

Q103 Would you classify/categorize this test as primarily a measure of: Neuromuscular control: the ability to accurately orchestrate a syncronized muscular response to internal and external perturbations based on sensory feedback Muscle capacity/performance: strength, endurance, or power of the involved musculature

- ❍ Neuromuscular control (1)
- ❍ Muscle capacity/performance (2)

- ❍ Mobility (3)
- ❍ None of these (4)

Q104 Which of the following body regions is this test primarily assessing? (you may select more than one)

- ❑ Upper extremity (1)
- ❑ Trunk/Pelvis (2)
- ❑ Lower extremity (3)

Q105 Do you think a difference in performance between sides is meaningful?

- ❍ Yes (1)
- ❍ No (2)

Answer If Do you think a difference in performance between sides is meaningful? If yes, what amount of difference would be meaningful? Yes Is Selected

Q106 You answered yes, a performance difference between sides is meaningful, what amount of difference would would you consider meaningful? Subtle: Questionable or mild differences between sidesObvious: Marked or clear differences between sides

- ❍ Subtle (1)
- ❍ Obvious (2)

Q107 Based on the following deviations from the expected performance of this test, drag over the TWO you would consider the most important and in ORDER of importance.

Click to write Group 1
______ Hips, knees, and ankles do not remain aligned in sagittal plane (1)
______ More than minimal movement is noted in lumbar spine or dowel (2)
______ Hurdle does not remain upright or leg does not clear tubing (3)
______ Loss of balance (4)

Q26 This test is performed by instructing the athlete to place the dowel along the spine so it touches the back of the head, upper back, and middle of the buttocks. While grasping the dowel at the neck and lumbar spine, the athlete is instructed to lower themselves into a lunge, touching the knee to the board and return to standing. In your opinion, which of the following constructs is this test primarily assessing? Stability: The ability to control the body region's position in order to withstand internal and external perturbations Mobility: Range of motion within one or multiple joints Movement pattern efficiency: the coordination of motion (timing and amount) between segments and/or extremities that demonstrates effective acceptance, generation, or transfer of forces to accomplish a skill or task. For bilateral tasks, this includes equal motion and weight bearing through the extremities

- ❍ Stability (1)
- ❍ Mobility (2)
- ❍ Movement pattern efficiency (3)

If Mobility Is Selected, Then Skip To Which of the following body regions i...

Q108 Would you classify/categorize this test as primarily a measure of: Neuromuscular control: the ability to accurately orchestrate a syncronized muscular response to internal and external perturbations based on sensory feedback Muscle capacity/performance: strength, endurance, or power of the involved musculature

- ❍ Neuromuscular control (1)
- ❍ Muscle capacity/performance (2)
- ❍ Mobility (3)
- ❍ None of these (4)

Q109 Which of the following body regions is this test primarily assessing? (you may select more than one)

- ❑ Upper extremity (1)
- ❑ Trunk/Pelvis (2)
- ❑ Lower extremity (3)

Q110 Do you think a difference in performance between sides is meaningful?

- ❍ Yes (1)
- ❍ No (2)

Answer If Do you think a difference in performance between sides is meaningful? If yes, what amount of difference would be meaningful? Yes Is Selected
Q111 You answered yes, a performance difference between sides is meaningful, what amount of difference would would you consider meaningful? Subtle: Questionable or mild differences between sidesObvious: Marked or clear differences between sides

- ❍ Subtle (1)
- ❍ Obvious (2)

Q112 Based on the following deviations from the expected performance of this test, drag over the THREE you would consider the most important and in ORDER of importance.

Click to write Group 1
______ Dowel does not remain in contact with trunk (1)
______ Trunk and dowel do not remain vertically aligned (2)
______ Feet do not remain in sagittal plane (3)
______ Knee does not touch board behind foot (4)
______ Subject loses balance (5)

Q181 This test is performed by instructing the athlete to stand tall, place the left palm on the front of the right shoulder, and then raise their left elbow as high as possible.   In your opinion, which of the following constructs is this test primarily assessing?   Stability: The ability to control the body region's position in order to withstand internal and external perturbations   Mobility: Range of motion within one or multiple joints   Movement pattern efficiency: the coordination of motion (timing and amount) between segments and/or extremities that demonstrates effective acceptance,

generation, or transfer of forces to accomplish a skill or task. For bilateral tasks, this includes equal motion and weight bearing through the extremities
- ❍ Stability (1)
- ❍ Mobility (2)
- ❍ Movement Pattern Efficiency (3)

If Mobility Is Selected, Then Skip To Based on the following deviations fro...

Q182 Would you classify/categorize this test as primarily a measure of:Neuromuscular control: the ability to accurately orchestrate a syncronized muscular response to internal and external perturbations based on sensory feedbackMuscle capacity/performance: strength, endurance, or power of the involved musculature
- ❍ Neuromuscular Control (1)
- ❍ Mobility (2)
- ❍ Muscle capacity/performance (3)
- ❍ None of the above (4)

Q183 Based on the following deviations from the expected performance of this test, drag over the ONE you would consider the most important.

Click to write Group 1
______ Limited motion (1)
______ Excessive motion (2)
______ Pain (3)

Q27 This test is performed by first instructing the athlete to make a fist so that their fingers are around their thumbs. Next, the athlete will place the right fist overhead and down their back as far as possible while simultaneously taking their left fist up their back as far as possible in one motion. The distance between the two closest bony prominences of the hands is recorded. In your opinion, which of the following constructs is this test primarily assessing? Stability: The ability to control the body region's position in order to withstand internal and external perturbations Mobility: Range of motion within one or multiple joints Movement pattern efficiency: the coordination of motion (timing and amount) between segments and/or extremities that demonstrates effective acceptance, generation, or transfer of forces to accomplish a skill or task. For bilateral tasks, this includes equal motion and weight bearing through the extremities
- ❍ Stability (1)
- ❍ Mobility (2)
- ❍ Movement pattern efficiency (3)

If Mobility Is Selected, Then Skip To Which of the following body regions i...

Q113 Would you classify/categorize this test as primarily a measure of: Neuromuscular control: the ability to accurately orchestrate a syncronized muscular response to internal and external perturbations based on sensory feedback Muscle capacity/performance: strength, endurance, or power of the involved musculature
- ❍ Neuromuscular control (1)

❍ Muscle capacity/performance (2)
❍ Mobility (3)
❍ None of these (4)

Q114 Which of the following body regions is this test primarily assessing? (you may select more than one)
❑ Upper extremity (1)
❑ Trunk/Pelvis (2)

Q115 Do you think a difference in performance between sides is meaningful?
❍ Yes (1)
❍ No (2)

Answer If Do you think a difference in performance between sides is meaningful? If yes, what amount of difference would be meaningful? Yes Is Selected
Q116 You answered yes, a performance difference between sides is meaningful, what amount of difference would would you consider meaningful? Subtle: Questionable or mild differences between sides (less than 4 inches)Obvious: Marked or clear differences between sides (over 4 inches)
❍ Subtle (1)
❍ Obvious (2)

Q28 This test is performed by measuring passive internal and external range of motion of the glenohumeral joint bilaterally.   In your opinion, which of the following constructs is this test primarily assessing?   Stability: The ability to control the body region's position in order to withstand internal and external perturbations   Mobility: Range of motion within one or multiple joints   Movement pattern efficiency: the coordination of motion (timing and amount) between segments and/or extremities that demonstrates effective acceptance, generation, or transfer of forces to accomplish a skill or task. For bilateral tasks, this includes equal motion and weight bearing through the extremities
❍ Stability (1)
❍ Mobility (2)
❍ Movement pattern efficiency (3)
If Mobility Is Selected, Then Skip To Which of the following body regions i...

Q118 Would you classify/categorize this test as primarily a measure of: Neuromuscular control: the ability to accurately orchestrate a syncronized muscular response to internal and external perturbations based on sensory feedback Muscle capacity/performance: strength, endurance, or power of the involved musculature
❍ Neuromuscular control (1)
❍ Muscle capacity/performance (2)
❍ Mobility (3)
❍ None of these (4)

Q119 Which of the following body regions is this test primarily assessing? (you may select more than one)

❑ Upper extremity (1)
❑ Trunk/Pelvis (2)

Q120 Do you think a difference in performance between sides is meaningful?
❍ Yes (1)
❍ No (2)

Answer If Do you think a difference in performance between sides is meaningful? If yes, what amount of difference would be meaningful? Yes Is Selected
Q121 You answered yes, a performance difference between sides is meaningful, what amount of difference would would you consider meaningful? Subtle: Questionable or mild differences between sides (less than 15 degrees) Obvious: Marked or clear differences between sides (greater than 15 degrees)
❍ Subtle (1)
❍ Obvious (2)

Q29 This test is performed by first instructing the athlete to stand in a natural and relaxed posture. From this position, with the elbows straight and the thumbs pointing up, they will raise and lower their arms (3 seconds up, 3 seconds down) for 5 repititions. They will perform 5 repititions straight out in front (sagittal plane) and 5 repititions out to the side (frontal plane). The testers are visually assessing scapular motion and position. In your opinion, which of the following constructs is this test primarily assessing? Stability: The ability to control the body region's position in order to withstand internal and external perturbations Mobility: Range of motion within one or multiple joints Movement pattern efficiency: the coordination of motion (timing and amount) between segments and/or extremities that demonstrates effective acceptance, generation, or transfer of forces to accomplish a skill or task. For bilateral tasks, this includes equal motion and weight bearing through the extremities
❍ Stability (1)
❍ Mobility (2)
❍ Movement pattern efficiency (3)
If Mobility Is Selected, Then Skip To Which of the following body regions i...

Q123 Would you classify/categorize this test as primarily a measure of: Neuromuscular control: the ability to accurately orchestrate a syncronized muscular response to internal and external perturbations based on sensory feedback Muscle capacity/performance: strength, endurance, or power of the involved musculature
❍ Neuromuscular control (1)
❍ Muscle capacity/performance (2)
❍ Mobility (3)
❍ None of these (4)

Q124 Which of the following body regions is this test primarily assessing? (you may select more than one)
❑ Upper extremity (1)
❑ Trunk/pelvis (2)

Q125 Do you think a difference in performance between sides is meaningful?
- ❍ Yes (1)
- ❍ No (2)

Answer If Do you think a difference in performance between sides is meaningful? If yes, what amount of difference would be meaningful? Yes Is Selected
Q126 You answered yes, a performance difference between sides is meaningful, what amount of difference would would you consider meaningful? Subtle: Questionable or mild differences between sidesObvious: Marked or clear differences between sides
- ❍ Subtle (1)
- ❍ Obvious (2)

Q127 Based on the following deviations from the expected performance of this test, drag over the TWO you would consider the most important

Click to write Group 1
______ Dysrhythmia on one or both sides (1)
______ Winging on one or both sides (2)
______ Asymmetrical performance (3)
______ Pain with performance (4)

Q30 This test is performed by first having the athlete start in the top position of a pushup, with the feet together and hands on each respective tape line (36 inches apart). From this position, the athlete leans over one hand and picks up the opposite hand reaches over to touch hands and then returns the hand to the starting position for a maximum number of touches in 15 seconds.   In your opinion, which of the following constructs is this test primarily assessing?   Stability: The ability to control the body region's position in order to withstand internal and external perturbations   Mobility: Range of motion within one or multiple joints   Movement pattern efficiency: the coordination of motion (timing and amount) between segments and/or extremities that demonstrates effective acceptance, generation, or transfer of forces to accomplish a skill or task. For bilateral tasks, this includes equal motion and weight bearing through the extremities
- ❍ Stability (1)
- ❍ Mobiilty (2)
- ❍ Movement pattern efficiency (3)

If Mobiilty Is Selected, Then Skip To Which of the following body regions i...

Q128 Would you classify/categorize this test as primarily a measure of: Neuromuscular control: the ability to accurately orchestrate a syncronized muscular response to internal and external perturbations based on sensory feedback Muscle capacity/performance: strength, endurance, or power of the involved musculature
- ❍ Neuromuscular control (1)
- ❍ Muscle capacity/performance (2)
- ❍ Mobility (3)

❍ None of these (4)

Q129 Which of the following body regions is this test primarily assessing? (you may select more than one)

❑ Upper extremity (1)
❑ Trunk/Pelvis (2)
❑ Lower extremity (3)

Q31 This test is performed by instructing the athlete to stand on a stool, feet hip width apart and arms across the chest. From this position, the athlete will step down as far as possible, attempting to touch the heel to the ground while maintaing the stance foot contact with the step. Performed 5 times consecutively on each leg. In your opinion, which of the following constructs is this test primarily assessing? Stability: The ability to control the body region's position in order to withstand internal and external perturbations Mobility: Range of motion within one or multiple joints Movement pattern efficiency: the coordination of motion (timing and amount) between segments and/or extremities that demonstrates effective acceptance, generation, or transfer of forces to accomplish a skill or task. For bilateral tasks, this includes equal motion and weight bearing through the extremities

❍ Stability (1)
❍ Mobility (2)
❍ Movement patter efficiency (3)

If Mobility Is Selected, Then Skip To Which of the following body regions i...

Q133 Would you classify/categorize this test as primarily a measure of: Neuromuscular control: the ability to accurately orchestrate a syncronized muscular response to internal and external perturbations based on sensory feedback Muscle capacity/performance: strength, endurance, or power of the involved musculature

❍ Neuromuscular control (1)
❍ Muscle capacity/performance (2)
❍ Mobility (3)
❍ None of these (4)

Q134 Which of the following body regions is this test primarily assessing? (you may select more than one)

❑ Upper extremity (1)
❑ Trunk/Pelvis (2)
❑ Lower extremity (3)

Q135 Do you think a difference in performance between sides is meaningful?

❍ Yes (1)
❍ No (2)

Answer If Do you think a difference in performance between sides is meaningful? If yes, what amount of difference would be meaningful? Yes Is Selected

Q136 You answered yes, a performance difference between sides is meaningful, what amount of difference would would you consider meaningful? Subtle: Questionable or mild differences between sidesObvious: Marked or clear differences between sides
- ❍ Subtle (1)
- ❍ Obvious (2)

Q137 Based on the following deviations from the expected performance of this test, drag over the FOUR you would consider the most important and in ORDER of importance.

Click to write Group 1
______ Pelvis does not remain in neutral (1)
______ Trunk does not remain in a neutral, vertically aligned position (2)
______ Knee collapses toward midline of the body (3)
______ Stance heel lifts from the step (4)
______ Asymmetrical performance between sides (5)
______ Motion is not performed smoothly (6)
______ Loss of balance (7)

Q32 This test is performed by instructing the athlete to stand on one foot and jump forward as far as possible, landing on the same leg they jumped off of. Athletes are required to hold the landing for at least 2 seconds.   In your opinion, which of the following constructs is this test primarily assessing?   Stability: The ability to control the body region's position in order to withstand internal and external perturbations   Mobility: Range of motion within one or multiple joints   Movement pattern efficiency: the coordination of motion (timing and amount) between segments and/or extremities that demonstrates effective acceptance, generation, or transfer of forces to accomplish a skill or task. For bilateral tasks, this includes equal motion and weight bearing through the extremities
- ❍ Stability (1)
- ❍ Mobility (2)
- ❍ Movement pattern efficiency (3)

If Mobility Is Selected, Then Skip To Which of the following body regions i...

Q138 Would you classify/categorize this test as primarily a measure of: Neuromuscular control: the ability to accurately orchestrate a syncronized muscular response to internal and external perturbations based on sensory feedback Muscle capacity/performance: strength, endurance, or power of the involved musculature
- ❍ Neuromuscular control (1)
- ❍ Muscle capacity/performance (2)
- ❍ Mobility (3)
- ❍ None of these (4)

Q139 Which of the following body regions is this test primarily assessing? (you may select more than one)
- ❑ Trunk/Pelvis (1)

❑ Lower extremity (2)

Q140 Do you think a difference in performance between sides is meaningful?
❍ Yes (1)
❍ No (2)

Answer If Do you think a difference in performance between sides is meaningful? If yes, what amount of difference would be meaningful? Yes Is Selected
Q141 You answered yes, a performance difference between sides is meaningful, what amount of difference would would you consider meaningful? Subtle: Questionable or mild differences between sides (less than 10% difference)Obvious: Marked or clear differences between sides (greater than 10% difference)
❍ Subtle (1)
❍ Obvious (2)

Q142 Based on the following deviations from the expected performance of this test, drag over the TWO you would consider the most important and in ORDER of importance.

Click to write Group 1
______ Trunk does not remain in neutral, presence of excessive forward or side flexion (1)
______ Knee collapses toward midline of body (2)
______ Lack of knee flexion on landing - stiff landing (3)

Q33 This test is performed with the athlete barefoot. While standing on one foot with the big toe at the beginning of the tape line, the athlete is instructed to reach out in front of them as far as possible and touch the tape line while keeping the stance heel in contact with the ground and hands on hips.   In your opinion, which of the following constructs is this test primarily assessing?   Stability: The ability to control the body region's position in order to withstand internal and external perturbations   Mobility: Range of motion within one or multiple joints   Movement pattern efficiency: the coordination of motion (timing and amount) between segments and/or extremities that demonstrates effective acceptance, generation, or transfer of forces to accomplish a skill or task. For bilateral tasks, this includes equal motion and weight bearing through the extremities
❍ Stability (1)
❍ Mobility (2)
❍ Movement pattern efficiency (3)
If Mobility Is Selected, Then Skip To Which of the following body regions i...

Q143 Would you classify/categorize this test as primarily a measure of: Neuromuscular control: the ability to accurately orchestrate a syncronized muscular response to internal and external perturbations based on sensory feedback Muscle capacity/performance: strength, endurance, or power of the involved musculature
❍ Neuromuscular control (1)
❍ Muscle capacity/performance (2)
❍ Mobility (3)

❍ None of these (4)

Q144 Which of the following body regions is this test primarily assessing? (you may select more than one)
❑ Lower extremity (1)
❑ Trunk/Pelvis (2)

Q145 Do you think a difference in performance between sides is meaningful?
❍ Yes (1)
❍ No (2)

Answer If Do you think a difference in performance between sides is meaningful? If yes, what amount of difference would be meaningful? Yes Is Selected
Q146 You answered yes, a performance difference between sides is meaningful, what amount of difference would would you consider meaningful?

Q34 This test is performed by placing a blood pressure cuff under the low back and the athlete lined up with a wall goniometer (hip joint at the axis). The athlete starts with the knees fully extended and hips flexed to 90 degrees. From this position, the athlete is instructed to lower their legs (while keeping them straight) towards the ground in a slow and controlled manner. When the pressure in the blood pressure cuff changes more than 10 mmHg, the angle at which the legs were when this occur is noted. In your opinion, which of the following constructs is this test primarily assessing? Stability: The ability to control the body region's position in order to withstand internal and external perturbations Mobility: Range of motion within one or multiple joints Movement pattern efficiency: the coordination of motion (timing and amount) between segments and/or extremities that demonstrates effective acceptance, generation, or transfer of forces to accomplish a skill or task. For bilateral tasks, this includes equal motion and weight bearing through the extremities
❍ Stability (1)
❍ Mobility (2)
❍ Movement pattern efficiency (3)
If Mobility Is Selected, Then Skip To Which of the following body regions i...

Q148 Would you classify/categorize this test as primarily a measure of: (you may select more than one) Neuromuscular control: the ability to accurately orchestrate a syncronized muscular response to internal and external perturbations based on sensory feedback Muscle capacity/performance: strength, endurance, or power of the involved musculature
❑ Neuromuscular control (1)
❑ Muscle capacity/performance (2)
❑ Mobility (3)
❑ None of these (4)

Q149 Which of the following body regions is this test primarily assessing? (you may select more than one)

❍ Trunk/pelvis (1)
❍ Lower extremity (2)

Q35 This test is performed by strapping the athlete to a table using three mobilization belts (one at the ankle, one proximal to the knee, one at the buttocks). The athlete lifts the torso so that it is parallel to the ground and is instructed to maintain this position for as long as possible. The test is terminated when a 10 degree change in trunk position occurs or the athlete stops on their own. In your opinion, which of the following constructs is this test primarily assessing? Stability: The ability to control the body region's position in order to withstand internal and external perturbations Mobility: Range of motion within one or multiple joints Movement pattern efficiency: the coordination of motion (timing and amount) between segments and/or extremities that demonstrates effective acceptance, generation, or transfer of forces to accomplish a skill or task. For bilateral tasks, this includes equal motion and weight bearing through the extremities
❍ Stability (1)
❍ Mobility (2)
❍ Movement pattern efficiency (3)
If Mobility Is Selected, Then Skip To Which of the following body regions i...

Q151 Would you classify/categorize this test as primarily a measure of: Neuromuscular control: the ability to accurately orchestrate a syncronized muscular response to internal and external perturbations based on sensory feedback Muscle capacity/performance: strength, endurance, or power of the involved musculature
❍ Neuromuscular control (1)
❍ Muscle capacity/performance (2)
❍ Mobility (3)
❍ None of these (4)

Q152 Which of the following body regions is this test primarily assessing? (you may select more than one)
❑ Trunk/pelvis (1)
❑ Lower extremity (2)

Q36 This test requires the athlete to sit in a hooklying position with a custom built 60 degree wedge placed behind their back. The wedge is pulled back slightly and the athlete is instructed to maintain this position for as long as possible. The test is terminated when the athlete changes their hip flexion angle by more than 5 degrees. In your opinion, which of the following constructs is this test primarily assessing? Stability: The ability to control the body region's position in order to withstand internal and external perturbations Mobility: Range of motion within one or multiple joints Movement pattern efficiency: the coordination of motion (timing and amount) between segments and/or extremities that demonstrates effective acceptance, generation, or transfer of forces to accomplish a skill or task. For bilateral tasks, this includes equal motion and weight bearing through the extremities
❍ Stability (1)
❍ Mobility (2)

❍ Movement pattern efficiency (3)
If Mobility Is Selected, Then Skip To Which of the following body regions i...

Q154 Would you classify/categorize this test as primarily a measure of: Neuromuscular control: the ability to accurately orchestrate a syncronized muscular response to internal and external perturbations based on sensory feedback Muscle capacity/performance: strength, endurance, or power of the involved musculature
❍ Neuromuscular control (1)
❍ Muscle capacity/performance (2)
❍ Mobility (3)
❍ None of these (4)

Q155 Which of the following body regions is this test primarily assessing? (you may select more than one)
❑ Trunk/pelvis (1)
❑ Lower extremity (2)

Q37 This test starts with the athlete sitting on a physioball (6 inches from a wall) with the arms across the chest, eyes open, and the feet on the ground. The athlete will then lift the feet from ground, maintaining heel contact with the ball and feet in front at all times. The test starts when the athlete's feet leave the ground and is terminated when the athlete's feet touch the ground again or the ball/body touches the wall behind them. The time the athlete is able to maintain the position shown below is recorded. In your opinion, which of the following constructs is this test primarily assessing? Stability: The ability to control the body region's position in order to withstand internal and external perturbations Mobility: Range of motion within one or multiple joints Movement pattern efficiency: the coordination of motion (timing and amount) between segments and/or extremities that demonstrates effective acceptance, generation, or transfer of forces to accomplish a skill or task. For bilateral tasks, this includes equal motion and weight bearing through the extremities
❍ Stability (1)
❍ Mobility (2)
❍ Movement pattern efficiency (3)
If Mobility Is Selected, Then Skip To Which of the following body regions i...

Q157 Would you classify/categorize this test as primarily a measure of: (you may select more than one) Neuromuscular control: the ability to accurately orchestrate a syncronized muscular response to internal and external perturbations based on sensory feedback Muscle capacity/performance: strength, endurance, or power of the involved musculature
❑ Neuromuscular control (1)
❑ Muscle capacity/performance (2)
❑ Mobility (3)
❑ None of these (4)

Q158 Which of the following body regions is this test primarily assessing? (you may select more than one)
- ❍ Trunk/pelvis (1)
- ❍ Lower extremity (2)

Q160 Do you believe the tests presented in this survey adequately cover all body regions?
- ❍ Yes (1)
- ❍ No (2)

Answer If Do you feel all body regions were adequately represented?   No Is Selected
Q163 You answered NO to the above question, which region do you believe is underrepresented? (you may select more than one)
- ❑ Upper extremity (1)
- ❑ Lower extremity (2)
- ❑ Trunk/pelvis (3)

Q161 Are there any other tests not presented here that you believe have value as an athletic screening tool?

Appendix 12. Survey #2

Survey of Opinions on Athletic Screening Tests_2

Q1 Survey of Opinions on Athletic Screening Tests In the first survey you were asked to make decisions regarding the test construct (stability, movement pattern efficiency or mobility), performance characteristic (muscle capacity, neuromuscular control, mobility), the region(s) being tested (trunk/pelvis, lower extremity) for 32 different clinical screening test used on athletes. You also were asked to indicate if asymmetrical performance (between sides) of the test had clinical meaningfulness. The results of the previous survey revealed that a majority of you agreed on the anatomical region that each test was assessing, the importance of asymmetry, and the test construct. The following five questions will provide the results of the previous survey as well as published or internal inter-rater reliability of each test. The results and questions are presented by anatomical region, broken down into the following categories: upper extremity, combined trunk/pelvis and upper extremity, lower extremity, combined trunk/pelvis and lower extremity, and trunk/pelvis. In the first survey, you were allowed to select if a test assessed more than one region. Therefore, tests were considered combined when over 50% of the responses included a second agreed upon region. Internally derived inter-rater reliability was completed on 80 athletes using two independent raters. Internal reliability was not available for some tests, thus, you are provided with published data regarding their reliability. Internally derived reliability was determined via observation of test performance based on whether a rater saw a deviation or not and was computed using the kappa statistic. As you complete the survey, please keep in mind that the goal of the comprehensive screen is to represent all constructs and performance characteristics across the major regions of the body. Key operational definitions are provided below: Movement pattern efficiency: the coordination of motion (timing and amount) between segments and/or extremities that demonstrates effective acceptance, generation, or transfer of forces to accomplish a skill or task. For bilateral tasks, this includes equal motion and weight bearing through the extremities   Stability: The ability to control the body region's position in order to withstand internal and external perturbations   Mobility: Range of motion within one or multiple joints   Muscle capacity: strength, endurance, or power of the involved musculature   Neuromuscular control: the ability to accurately orchestrate a synchronized muscular response to internal and external perturbations based on sensory feedback   A back button is provided in the event you would like to change or review a response.

Q11 The following chart contains the results of all tests classified as primarily assessing the UPPER EXTREMITY region. Based on this data AND your clinical experience, please rank (by dragging the test names over in the box below) the following tests in the order in which you think they provide the most information or are the better assessments to include in a comprehensive pre-participation screen for this region.   *Photos are shown as a reminder of test performance.

Please rank here

______ Shoulder Clearing Test (1)
______ Shoulder Mobility (2)
______ Glenohumeral Internal Rotation Deficit (GIRD) (3)
______ Scapular Dyskinesis (4)

Q10 The following chart contains the results of all tests classified as primarily assessing the COMBINED TRUNK/PELVIS AND UPPER EXTREMITY region. Based on this data AND your clinical experience, please rank the following tests in the order in which you think they provide the most information or are the better assessments to include in a comprehensive pre-participation screen for this region.   Note the following abbreviations: MPE = movement pattern efficiency NMC = neuromuscular control k = kappa   *Photos are shown as a reminder of test performance.

Please Rank Here

______ Closed Kinetic Chain Upper Extremity Stability Test (1)
______ Trunk Stability Push-Up (2)

Q13 The following chart contains the results of all tests classified as primarily assessing the LOWER EXTREMITY region. Based on this data AND your clinical experience, please rank the following tests in the order in which you think they provide the most information or are the better assessments to include in a comprehensive pre-participation screen for this region.   Note the following abbreviations: MPE = movement pattern efficiency NMC = neuromuscular control k = kappa   *Photos are shown as a reminder of test performance.

Please rank here

______ Active Straight Leg Raise (1)

______ Single Leg Hop (2)
______ Y-Balance Test (anterior direction) (3)

Q12 The following chart contains the results of all tests classified as primarily assessing the COMBINED TRUNK/PELVIS AND LOWER EXTREMITY region. Based on this data AND your clinical experience, please pick the 4 tests (rank order by dragging test names over into the top box below) that you think are the most informative or best assessments to include in a comprehensive pre-participation screen for this region. After you have selected your 4 tests, please move the remaining tests to the lower box (labeled "All other tests") in rank order preference. *Photos are shown as a reminder of test performance.

Tests to keep here (in rank order) (4)	All other tests (9)
______ Active Hip Abduction (1)	______ Active Hip Abduction (1)
______ Active Hip Abduction Resisted (2)	______ Active Hip Abduction Resisted (2)
______ Modified Thomas Test (3)	______ Modified Thomas Test (3)
______ Hip Bridge with Lower Extremity Extension (4)	______ Hip Bridge with Lower Extremity Extension (4)
______ Hip Bridge with Lower Extremity Extension Resisted (5)	______ Hip Bridge with Lower Extremity Extension Resisted (5)
______ Unilateral Hip Bridge Endurance (6)	______ Unilateral Hip Bridge Endurance (6)
______ Prone Hip Extension (7)	______ Prone Hip Extension (7)
______ Prone Hip Extension with Contralateral Arm Lift (8)	______ Prone Hip Extension with Contralateral Arm Lift (8)
______ Flexor Clearing Test (9)	______ Flexor Clearing Test (9)
______ Overhead Squat (10)	______ Overhead Squat (10)
______ Hurdle Step (11)	______ Hurdle Step (11)
______ In-Line Lunge (12)	______ In-Line Lunge (12)
______ Step Down (13)	______ Step Down (13)

Q9 The following chart contains the results of all tests classified as primarily assessing the TRUNK/PELVIS region. Based on this data AND your clinical experience, please pick the 4 tests (rank order by dragging test names over into the top box below) that you think are the most informative or best assessments to include in a comprehensive pre-participation screen for this region. After you have selected your 4 tests, please move the remaining tests to the lower box (labeled "All other tests") in rank order preference. *Photos are shown as a reminder of test performance.

Tests to keep here (in rank order) (4)	All other tests here (6 tests)
______ Side Bridge (4)	______ Side Bridge (4)
______ Side Bridge with Active Hip Abduction (5)	______ Side Bridge with Active Hip Abduction (5)
______ Side Bridge with Active Hip Abduction Resisted (14)	______ Side Bridge with Active Hip Abduction Resisted (14)

_______ Bird Dog (6)
_______ Rotary Stability (7)
_______ Extension Clearing Test (8)
_______ Double Leg Lowering Test (9)
_______ Trunk Extensor Endurance (10)
_______ Trunk Flexor Endurance (11)
_______ Clinical Core Control Test (12)

_______ Bird Dog (6)
_______ Rotary Stability (7)
_______ Extension Clearing Test (8)
_______ Double Leg Lowering Test (9)
_______ Trunk Extensor Endurance (10)
_______ Trunk Flexor Endurance (11)
_______ Clinical Core Control Test (12)

Appendix 13. Breakdown of Survey Results

Survey #1

Test: AHA

	Constructs			**Region**		**Asymmetry**			
Answer	%	Answer	%	Answer	%	Answer	%	Answer	%
Stability	38%	Neuromuscular Control	50%	Trunk/Pelvis	62%	Yes	92%	Subtle	17%
Mobility	8%	Muscle Capacity/Performance	58%	Hip	77%	No	8%	Obvious	83%
Movement Pattern Efficiency	54%	Mobility	0%	Lower Extremity	8%	Total	100%	Total	100%
Total	100%	None of these	0%		100%				
			100%						

Test: AHAR

	Constructs			**Region**		**Asymmetry**			
Answer	%	Answer	%	Answer	%	Answer	%	Answer	%
Stability	100%	Neuromuscular Control	10%	Trunk/Pelvis	50%	Yes	100%	Subtle	20%
Mobility	0%	Muscle Capacity/Performance	90%	Hip	90%	No	0%	Obvious	80%
Movement Pattern Efficiency	0%	Mobility	0%	Lower Extremity	10%	Total	100%	Total	100%
Total	100%	None of these	0%	Total	100%				
		Total	100%						

Test: SB

	Constructs			**Region**		**Asymmetry**			
Answer	%	Answer	%	Answer	%	Answer	%	Answer	%
Stability	70%	Neuromuscular	20%	Trunk/pelvis	100%	Yes	100%	Subtle	20%

		Control							
Mobility	0%	Muscle capacity/peformance	80%	Shoulder	0%	No	0%	Obvious	80%
Movement pattern efficiency	30%	Mobility	0%	Lower extremity	0%	Total	100%	Total	100%
Total	100%	None of these	0%	Total	100%				

Test:

SBABD

Constructs				Region		Asymmetry			
Answer	%	Answer	%	Answer	%	Answer	%	Answer	%
Stability	40%	Neuromuscular control	80%	Trunk/Pelvis	100%	Yes	100%	Subtle	20%
Mobility	0%	Muscle capacity/performance	20%	Shoulder	0%	No	0%	Obvious	80%
Movement Pattern Efficiency	60%	Mobility	0%	Lower Extremity	0%	Total	100%	Total	100%
Total	100%	None of these	0%	Total	100%				
		Total	100%						

Test: SBABDR

Constructs				Region		Asymmetry			
Answer	%	Answer	%	Answer	%	Answer	%	Answer	%
Stability	90%	Neuromuscular Control	40%	Trunk/Pelvis	80%	Yes	100%	Subtle	20%
Mobility	0%	Muscle capacity/performance	60%	Shoulder	0%	No	0%	Obvious	80%
Movement pattern efficiency	10%	Mobility	0%	Lower Extremity	40%	Total	100%	Total	100%
Total	100%	None of these	0%	Total	100%				

Test: MTT

Constructs		Region		Asymmetry			
Answer	%	Answer	%	Answer	%	Answer	%
Stability	0%	Trunk/Pelvis	0%	Yes	89%	Subtle	13%
Mobility	100%	Lower extremity	44%	No	11%	Obvious	88%
Movement pattern efficiency	0%	Both	56%	Total	100%	Total	100%
Total	100%	Total	100%				

Test: ASLR

Constructs		Region		Asymmetry			
Answer	%	Answer	%	Answer	%	Answer	%
Stability	0%	Trunk/pelvis	0%	Yes	89%	Subtle	13%

Mobility	100%	Lower extremity	67%	No	11%	Obvious	88%
Movement pattern efficiency	0%	Both	33%	Total	100%	Total	100%
Total	100%	Total	100%				

Test: HBEXT

Constructs				Region		Asymmetry			
Answer	%	Answer	%	Answer	%	Answer	%	Answer	%
Stability	67%	Neuromuscular Control	44%	Trunk/Pelvis	22%	Yes	100%	Subtle	33%
Mobility	0%	Muscle capacity/performance	56%	Lower Extremity	11%	No	0%	Obvious	67%
Movement pattern efficiency	33%	Mobility	0%	Both	67%	Total	100%	Total	100%
Total	100%	None of these	0%	Total	100%				
		Total	100%						

Test: HBEXTR

Constructs				Region		Asymmetry			
Answer	%	Answer	%	Answer	%	Answer	%	Answer	%
Stability	100%	Neuromuscular control	33%	Trunk/pelvis	22%	Yes	100%	Subtle	33%
Mobility	0%	Muscle capacity/performance	67%	lower extremity	11%	No	0%	Obvious	67%
Movement pattern efficiency	0%	Mobility	0%	Both	67%	Total	100%	Total	100%
Total	100%	None of these	0%	Total	100%				

Test: UHBE

Constructs				Region		Asymmetry			
Stability	100%	Neuromuscular control	44%	Answer	%	Yes	89%	Answer	%
Mobility	0%	Muscle capacity/performance	56%	Trunk/pelvis	33%	No	11%	Subtle	38%
Movement pattern efficiency	0%	Mobiilty	0%	lower extremity	0%	Total	100%	Obvious	63%
Total	100%	None of these	0%	Both	67%			Total	100%
		Total	100%	Total	100%				

Test: HIPEXT

Constructs				Region		Asymmetry			
Answer	%	Answer	%	Answer	%	Answer	%	Answer	%
Stabilty	33%	Neuromuscular control	50%	Trunk/Pelvis	33%	Yes	100%	Subtle	11%
Mobility	11%	Muscle capacity/performance	25%	Lower Extremity	11%	No	0%	Obvious	89%

Movement pattern efficiency	56%	Mobility	25%	Both	56%	Total	100%	Total	100%
Total	100%	None of these	0%	Total	100%				

Test: HIPEXTarm

	Constructs			Region		Asymmetry			
Answer	%	Answer	%	Answer	%	Answer	%	Answer	%
Stability	56%	Neuromuscular control	78%	Trunk/Pelvis	100%	Yes	100%	Subtle	11%
Mobility	0%	Muscle capacity/performance	22%	Lower extremity	0%	No	0%	Obvious	89%
Movement pattern efficiency	44%	Mobility	0%	Upper extremity	0%	Total	100%	Total	100%
Total	100%	None of these	0%	Total	100%				
		Total	100%						

Test: FLEX

	Constructs			Region		Asymmetry
Answer	%	Answer	%	Answer	%	
Stability	11%	Neuromuscular Control	100%	Trunk/Pelvis	100%	
Mobility	67%	Mobility	0%	Upper Extremity	33%	
Movement Pattern Efficiency	22%	Muscle capacity/performance	0%	Lower Extremity	44%	
Total	100%	Total	100%		100%	

Test: BIRD DOG

	Constructs			Region		Asymmetry			
Answer	%	Answer	%	Answer	%	Answer	%	Answer	%
Stability	11%	Neuromuscular Control	89%	Upper Extremity	11%	Yes	78%	Subtle	14%
Mobility	0%	Muscle Capacity/Performance	11%	Lower Extremity	11%	No	22%	Obvious	86%
Movement Pattern Efficiency	89%	Mobility	0%	Trunk/Pelvis	100%	Total	100%	Total	100%
Total	100%	Total	100%		100%				

Test: ROT STAB

	Constructs			Region		Asymmetry			
Answer	%	Answer	%	Answer	%	Answer	%	Answer	%
Stability	38%	Neuromuscular control	88%	Trunk/Pelvis	100%	Yes	75%	Subtle	17%
Mobility	0%	Muscle capacity/performance	13%	Lower Extremity	25%	No	25%	Obvious	83%
Movement Pattern Efficiency	63%	Mobility	0%	Upper extremity	25%	Total	100%	Total	100%

Total	100%	None of these	0%		100%

Test: PUSHUP

Constructs				Region	
Answer	%	Answer	%	Answer	%
Stability	63%	Neuromuscular control	75%	Trunk/Pelvis	100%
Mobility	0%	Muscle capacity/performance	25%	Upper extremity	63%
Movement pattern efficiency	38%	Mobility	0%	Lower extremity	13%
Total	100%	None of these	0%		100%

Test: SQUAT

Constructs				Region	
Answer	%	Answer	%	Answer	%
Stability	25%	Neuromuscular control	67%	Upper extremity	25%
Mobility	25%	Muscle capacity/performance	17%	Trunk/Pelvis	88%
Movement pattern efficiency	50%	Mobility	0%	Lower extremity	75%
Total	100%	None of these	17%		100%

Test: HURDLE

Constructs				Region		Asymmetry			
Answer	%	Answer	%	Answer	%	Answer	%	Answer	%
Stability	25%	Neuromuscular control	100%	Upper extremity	0%	Yes	88%	Subtle	29%
Mobility	13%	Muscle capacity/performance	0%	Trunk/Pelvis	63%	No	13%	Obvious	71%
Movement pattern efficiency	63%	Mobility	0%	Lower extremity	88%	Total	100%	Total	100 %
Total	100%	None of these	0%		100%				
		Total	100%						

Test: LUNGE

Constructs				Region		Asymmetry			
Answer	%	Answer	%	Answer	%	Answer	%	Answer	%
Stability	25%	Neuromuscular control	86%	Upper extremity	13%	Yes	88%	Subtle	17%
Mobility	13%	Muscle capacity/performance	14%	Trunk/Pelvis	75%	No	13%	Obvious	83%
Movement pattern efficiency	63%	Mobility	0%	Lower extremity	75%	Total	100%	Total	100 %
Total	100%	None of these	0%		100%				

Test: SHO MOB

Constructs		Region		Asymmetry			
Answer	%	Answer	%	Answer	%	Answer	%
Stability	0%	Upper extremity	100%	Yes	88%	Subtle	14%
Mobility	100%	Trunk/Pelvis	13%	No	13%	Obvious	86%
Movement pattern efficiency	0%		100%	Total	100%	Total	100 %
Total	100%						

Test: GIRD

Constructs		Region		Asymmetry			
Answer	%			Answer	%	Answer	%
Stability	0%			Yes	100%	Subtle	38%
Mobility	100%			No	0%	Obvious	63%
Movement pattern efficiency	0%			Total	100%	Total	100 %
Total	100%						

Test: SCAP DYSK

Constructs				Region		Asymmetry			
Answer	%	Answer	%	Answer	%	Answer	%	Answer	%
Stability	13%	Neuromuscular control	100%	Upper extremity	100%	Yes	86%	Subtle	17 %
Mobility	0%	Muscle capacity/performance	0%	Trunk/pelvis	13%	No	14%	Obvious	83 %
Movement pattern efficiency	88%	Mobility	0%		100%	Total	100%	Total	100 %
Total	100%	None of these	0%						
		Total	100%						

Test: CKCUEST

Constructs				Region		Asymmetry
Answer	%	Answer	%	Answer	%	
Stability	43%	Neuromuscular control	43%	Upper extremity	86%	
Mobiilty	0%	Muscle capacity/performance	57%	Trunk/Pelvis	71%	
Movement pattern efficiency	57%	Mobility	0%	Lower extremity	29%	
Total	100%	None of these	0%		100%	

Test: STEP DOWN

Constructs				Region		Asymmetry			
Answer	%	Answer	%	Answer	%	Answer	%	Answer	%
Stability	13%	Neuromuscular control	100%	Upper extremity	0%	Yes	100%	Subtle	38 %

Mobility	0%	Muscle capacity/performance	0%	Trunk/Pelvis	63%	No	0%	Obvious	63 %
Movement patter efficiency	88%	Mobility	0%	Lower extremity	100%	Total	100%	Total	100 %
Total	100%	None of these	0%		100%				
		Total	100%						

Test: HOP

Constructs				Region		Asymmetry			
Answer	%	Answer	%	Answer	%	Answer	%	Answer	%
Stability	25%	Neuromuscular control	25%	Trunk/Pelvis	38%	Yes	100%	Subtle	0%
Mobility	0%	Muscle capacity/performance	63%	Lower extremity	100%	No	0%	Obvious	100 %
Movement pattern efficiency	75%	Mobility	0%		100%	Total	100%	Total	100 %
Total	100%	None of these	13%						
		Total	100%						

Test: YBT

Constructs				Region		Asymmetry		
Answer	%	Answer	%	Answer	%	Answer	%	25%
Stability	38%	Neuromuscular control	100%	Lower extremity	100%	Yes	88%	> 4 cm between sides
Mobility	13%	Muscle capacity/performance	0%	Trunk/Pelvis	50%	No	13%	> 10cm
Movement pattern efficiency	50%	Mobility	0%		100%	Total	100%	Obvious
Total	100%	None of these	0%					15%

Test: DLLT

Constructs				Region	
Answer	%	Answer	%	Answer	%
Stability	50%	Neuromuscular control	50%	Trunk/pelvis	100%
Mobility	0%	Muscle capacity/performance	50%	Lower extremity	0%

Movement pattern efficiency	50%	Mobility	0%	Total	100%
Total	100%	None of these	0%		
Test: TEE			100%		
	Constructs			**Region**	
Answer	%	Answer	%	Answer	%
Stability	88%	Neuromuscular control	0%	Trunk/pelvis	100%
Mobility	0%	Muscle capacity/performance	100%	Lower extremity	13%
Movement pattern efficiency	13%	Mobility	0%		100%
Total	100%	None of these	0%		
Test: TFE		Total	100%		
	Constructs			**Region**	
Answer	%	Answer	%	Answer	%
Stability	88%	Neuromuscular control	0%	Trunk/pelvis	100%
Mobility	0%	Muscle capacity/performance	100%	Lower extremity	0%
Movement pattern efficiency	13%	Mobility	0%		
Total	100%	None of these	0%		
		Total	100%		
Test: CCCT					
	Constructs			**Region**	
Answer	%	Answer	%	Answer	%
Stability	75%	Neuromuscular control	63%	Trunk/pelvis	100%
Mobility	0%	Muscle capacity/performance	38%	Lower extremity	0%
Movement pattern efficiency	25%	Mobility	0%	Total	100%
Total	100%	None of these	13%		
			100%		

VITAE
Courtney Butowicz, PhD (c), MSEd, CSCS

EDUCATION

BS	Old Dominion University, Norfolk, VA Major: Exercise Science	May 2005
MSEd	Old Dominion University, Norfolk, VA Major: Exercise Science Advisor: Jimmy Onate, PhD, ATC	May 2009
PhD	Drexel University, Philadelphia, PA Major: Rehabilitation Sciences Dissertation: Comprehensive performance-based movement-based screening tool for athletes. Advisor: Sheri Silfies, PhD, PT	June 2016

EMPLOYMENT

Post Doctoral Researcher July 2016
Walter Reed National Medical Center, Military Advanced Training Center
Bethesda, MD
Research Assistant
Drexel University, Philadelphia, PA 3/2013-Present
Department of Physical Therapy and Rehabilitation Sciences
College of Nursing and Health Professions Internal Research Grant (Finley, PI)
Legacy Fund Grant (Silfies, Co-PI)

PEER REVIEWED PUBLICATIONS

Butowicz CM, Ebaugh D, Noehren B, & Silfies SP. Validation of Two Clinical Measures of Core Stability. *International Journal of Sports Physical Therapy*. 2016: 11(1), 15-23.

Silfies SP, Ebaugh D, Pontillo M, **Butowicz CM.** Critical review of the impact of core stability on upper extremity athletic injury and performance. *Brazilian Journal of Physical Therapy*. 2015: 19(5), 360-368. [Impact factor: 0.979; Citations: 1]

Swain, DP, Ringleb, SI, Naik, DN, & **Butowicz, CM**. Effect of training with and without a load on military fitness tests and marksmanship. *The Journal of Strength & Conditioning Research*, 2011: 25(7), 1857-1865. [Impact factor: 2.075; Citations: 6]

Manuscripts in Progress

Butowicz, C.M., Ebaugh, D., Silfies, S.P. Measuring Core Stability in Athletes: Convergent and Divergent Validity of Current and Novel Clinical Measures. (*International Journal of Sports Physical Therapy).*

Butowicz, C.M., Ebaugh, D., Silfies, S.P. Differences in Movement System Screening Performance in Athletes With and Without Shoulder Pain (*Journal of Orthopedic and Sports Physical Therapy*).

Butowicz, C.M., Ebaugh, D., Silfies, S.P. Construct Validity and Reliability of a Novel Movement Screen for Athletes (*Journal of Strength and Conditioning Research).*